Indoor Environment Department

Publications 1995-2004

Introduction

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Several individuals contributed to the development of this bibliography. We thank Brian Smith, David Lorenzetti, and Sondra Jarvis for their important technical contributions. Olivia Salazar deserves our special thanks for her many hours of work assembling, updating, correcting, and entering the text.

Table of Contents

1. Aerosols, Indoor and Outdoor

Price, P. N. "Assessing uncertainties in the relationship between inhaled particle concentration, internal deposition and health effects." Submitted as a chapter to Aerosols Handbook: Measurement, Dosimetry and Health Effects, CRC Press, Boca Raton, FL. 2004. LBNL-53480 .

Abstract. The question that ultimately motivates most aerosol inhalation research is: for a given inhaled atmosphere, what health effects will result in a specified population? To attempt to address this question, quantitative research on inhaled aerosols has been performed for at least fifty years (Landahl et al, 1951). The physical factors that determine particle deposition have been determined, lung morphology has been quantified (particularly for adults), models of total particle deposition have been created and validated, and a large variety of inhalation experiments have been performed. However many basic questions remain, some of which are identified by the U.S. Committee on Research Priorities for Airborne Particulate Matter (NRC 1998a) as high-priority research areas. Among these are: What are the quantitative relationships between outdoor concentrations measured at stationary monitoring stations, and actual personal exposures? What are the exposures to biologically important constituents of particulate matter that cause responses in potentially susceptible subpopulations and the general population? What is the role of physicochemical characteristics of particulate matter in causing adverse health effects? As these questions show, in spite of significant progress in all areas of aerosol research, many of the most important practical questions remain unanswered or inadequately answered. In this chapter, we discuss the sources and magnitudes of error that hinder the ability to answer basic questions concerning the health effects of inhaled aerosols. We first consider the phenomena that affect the epidemiological studies, starting with studies of residential radon and moving on to fine particle air pollution. Next we discuss the major uncertainties in physical and physiological modeling of the causal chain that leads from inhaled aerosol concentration, to deposition in the airway, to time-dependent dose (that is, the concentration of particles at a given point in the lungs as function of time), to physiological effects, and finally to health effect.

Thatcher, Tracy L.; Lunden, Melissa M.; Revzan, Kenneth L.; Sextro, Richard G.; Brown, Nancy J. "A concentration rebound method for measuring particle penetration and deposition in the indoor environment." Aerosol Science & Technology, Volume 37, Pages 847-864. 2003. LBNL-51631 .

Abstract. Continuous, size resolved particle measurements were performed in two houses in order to determine size- dependent particle penetration into and deposition in the indoor environment. The experiments consisted of three parts: (1) measurement of the particle loss rate following artificial elevation of indoor particle concentrations, (2) rapid reduction in particle concentration through induced ventilation by pressurization of the houses with HEPA-filtered air, and (3) measurement of the particle concentration rebound after house pressurization stopped. During the particle concentration decay period, when indoor concentrations are very high, losses due to deposition are large compared to gains due to particle infiltration. During the concentration rebound period, the opposite is true. The large variation in indoor concentration allows the effects of penetration and deposition losses to be separated by the transient, two-parameter model we employed to analyze the data. For the two houses studied, we found that as particles increased in diameter from 0.1 to 10 μm, penetration factors ranged from 1 to 0.3 and deposition loss rates ranged from 0.1 and 5 h-1. The decline in penetration factor with increasing particle size was less pronounced in the house with the larger normalized leakage area.

Sippola, Mark R.; Nazaroff, William W. "Particle Deposition from Turbulent Flow: Review of Published Research and Its applicability to Ventilation Ducts in Commercial Buildings." 2003. LBNL-51432 .

Abstract. This report reviews published experimental and theoretical investigations of particle deposition from turbulent flows and considers the applicability of this work to the specific case of particle deposition from flows in the ducts of heating, ventilating and air conditioning (HVAC) systems. Particle deposition can detrimentally affect the performance of HVAC systems and it influences the exposure of building occupants to a variety of air pollutants. The first section of this report describes the types of HVAC systems under consideration and discusses the components,

materials, and operating parameters commonly found in these systems. The second section reviews published experimental investigations of particle deposition rates from turbulent flows and considers the ramifications of the experimental evidence with respect to HVAC ducts. The third section considers the structure of turbulent airflows in ventilation ducts with a particular emphasis on turbulence investigations that have been used as a basis for particle deposition models. The final section reviews published literature on predicting particle deposition rates from turbulent flows.

Sippola, Mark R. "Particle Deposition in Ventilation Ducts." 2003. LBNL-52189 .

Abstract. Exposure to airborne particles is detrimental to human health and indoor exposures dominate total exposures for most people. The accidental or intentional release of aerosolized chemical and biological agents within or near a building can lead to exposures of building occupants to hazardous agents and costly building remediation. Particle deposition in heating, ventilation and air-conditioning (HVAC) systems may significantly influence exposures to particles indoors, diminish HVAC performance and lead to secondary pollutant release within buildings. This dissertation advances the understanding of particle behavior in HVAC systems and the fates of indoor particles by means of experiments and modeling.

Sippola, M.R.; Nazaroff, W.W. "Modeling particle loss in ventilation ducts." Atmospheric Environment, Volume 37, Pages 5597-5610. 2003. LBNL-52449 .

Abstract. Empirical equations were developed and applied to predict losses of 0.01-100 μm airborne particles making a single pass through 120 different ventilation duct runs typical of those found in mid-sized office buildings. For all duct runs, losses were negligible for submicron particles and nearly complete for particles larger than 50 μm. The 50th percentile cut-point diameters were 15 μm in supply runs and 25 μm in return runs. Losses in supply duct runs were higher than in return duct runs, mostly because internal insulation was present in portions of supply duct runs, but absent from return duct runs. Single-pass equations for particle loss in duct runs were combined with models for predicting ventilation system filtration efficiency and particle deposition to indoor surfaces to evaluate the fates of particles of indoor and outdoor origin in an archetypal mechanically ventilated building. Results suggest that duct losses are a minor influence for determining indoor concentrations for most particle sizes. Losses in ducts were of a comparable magnitude to indoor surface losses for most particle sizes. For outdoor air drawn into an unfiltered ventilation system, most particles smaller than 1 mm are exhausted from the building. Large particles deposit within the building, mostly in supply ducts or on indoor surfaces. When filters are present, most particles are either filtered or exhausted. The fates of particles generated indoors follow similar trends as outdoor particles drawn into the building.

Sippola, M.R.; Nazaroff, W.W. "Experiments Measuring Particle Deposition from Fully Developed Turbulent Flow in Ventilation Ducts." Submitted to Aerosol Science and Technology. 2003. LBNL-53585 .

Abstract. Particle deposition in ventilation ducts influences particle exposures of building occupants and may lead to a variety of indoor air quality concerns. Experiments have been performed in a laboratory to study the effects of particle size and air speed on deposition rates of particles from turbulent air flows in galvanized steel and internally insulated ducts with hydraulic diameters of 15.2 cm. The duct systems were constructed of materials typically found in commercial heating, entilating and air conditioning (HVAC) systems. In the steel duct system, experiments with nominal particle sizes of 1, 3, 5, 9 and 16 μm were conducted at each of three nominal air speeds: 2.2, 5.3 and 9.0 m/s. In the insulated duct system, deposition rates of particles with nominal sizes of 1, 3, 5, 8 and 13 μm were measured at nominal air speeds of 2.2, 5.3 and 8.8 m/s. Fluorescent techniques were used to directly measure the deposition velocities of monodisperse fluorescent particles to duct surfaces (floor, wall and ceiling) at two straight duct sections where the turbulent flow profile was fully developed. In steel ducts, deposition rates were higher to the duct floor than to the wall, which were, in turn, greater than to the ceiling. In insulated ducts, deposition was nearly the same to the duct floor, wall and ceiling for a given particle size and air speed. Deposition to duct walls and ceilings was greatly enhanced in insulated ducts compared to steel ducts. Deposition velocities to each of the three duct surface orientations in both systems were found to increase with increasing particle

size or air velocity over the ranges studied. Deposition rates measured in the current experiments were in general agreement with the limited observations of similar systems by previous researchers.

Shendell, D.G.; Prill, R.; Fisk, W.J.; Apte, M.G.; Blake, D.; Faulkner, D. "Associations between classroom CO2 concentrations and student attendance." 2003. LBNL-53586 .

Abstract. Student attendance in American public schools is a critical factor in securing limited operational funding. Student and teacher attendance influence academic performance. Limited data exist on indoor air and environmental quality (IEQ) in schools, and how IEQ affects attendance, health, or performance. This study explored the association of student absence with measures of indoor minus outdoor carbon dioxide concentration (dCO2). Absence and dCO2 data were collected from 409 traditional and 25 portable classrooms from 14 schools located in six school districts in the states of Washington and Idaho. Study classrooms had individual heating, ventilation, and air conditioning (HVAC) systems, except two classrooms without mechanical ventilation. Classroom attributes, student attendance and school-level ethnicity, gender, and socioeconomic status (SES) were included in multivariate modeling. Forty-five percent of classrooms studied had short-term indoor CO2 concentrations above 1000 parts-per-million (ppm). A 1000 ppm increase in dCO2 was associated (p¡ 0.05) with a 0.5% to 0.9% decrease in annual average daily attendance (ADA), corresponding to a relative 10% to 20% increase in student absence. Outside air (ventilation) rates estimated from dCO2 and other collected data were not associated with absence. Annual ADA was 2% higher (p ¡ 0.0001) in traditional than in portable classrooms.

Lunden, M.M.; Revzan, K. L.; Fisher, M.L.; Thatcher, T.L.; Littlejohn, D.; Hering, S.V.; Brown, N.J. "The Transformation of Outdoor Ammonium Nitrate Aerosols in the Indoor Environment." Atmospheric Environment, Volume 37, Pages 5633-5644. 2003. LBNL-52795 .

Abstract. No abstract available

Lunden, M.M.; Thatcher, T.L.; Hering, S.V.; Brown, N.J. "Use of time- and chemically resolved particulate data to characterize the infiltration of outdoor PM2.5 into a residence in the San Joaquin Valley." Environmental Science and Technology, Volume 37, Pages 4724-4732. 2003. LBNL-52221 .

Abstract. No abstract available.

Fisk, W.J.; Faulkner, D.; Palonen, J.; Seppänen, O. "Performance and Costs of Particle Air Filtration in HVAC Supply Airstreams." HPAC Engineering, Volume 75, Pages 24-36. 2003. LBNL-53212 .

Abstract. This paper uses a model, and data on particle size distributions, filter efficiencies, and particle deposition rates to estimate the reductions in the indoor mass concentrations of particles attainable from use of filters in HVAC supply airstreams. Additionally, the energy and total costs of the filtration options are estimated. Predicted reductions in cat and dust-mite allergen concentrations range from 20% to 60%. Increasing filter efficiencies above approximately ASHRAE Dust Spot 65% (MERV 11) does not significantly reduce predicted indoor concentrations of these allergens. For environmental tobacco smoke particles and outdoor fine mode particles, calculations indicate that relatively large, e.g., 80%, decreases in indoor concentrations are attainable with practical filter efficiencies. Increasing the filter efficiency above ASHRAE Dust Spot 85% (MERV 13) results in only modest incremental decreases in concentrations. Energy costs and total costs do not always increase for higher efficiency filters. Total estimated filtration costs of $0.70 to $1.80 per person per month are insignificant relative to salaries, rent, or health insurance costs.

Thatcher, T.L.; Lunden, M.M.; Sextro, R.G.; Hering, S.; Brown, N.J. "The effect of penetration factor, deposition, and environmental factors on the indoor concentration of pm2.5 sulfate, nitrate, and carbon." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 846-851, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-50160 .

Abstract. Indoor exposure to particles of outdoor origin constitutes an important exposure pathway. We conducted an intensive set of indoor particle measurements in an unoccupied house under differing operating conditions. Real-time measurements were conducted both indoors and outdoors, including PM2.5 nitrate, sulfate, and carbon. Because the time-scale of the fluctuations in outdoor

particle concentrations and meteorological conditions are often similar to the time constant for building air exchange, a steady state concentration may never be reached. The time-series experimental data were used to determine the effect of changes in air exchange rate and indoor/outdoor temperature and relative humidity differences on indoor particle concentrations. A multivariate regression was performed to investigate the difference between measured indoor concentrations and results from a simple time-dependent physical model. Environmental conditions had a significant effect on indoor concentrations of all three PM2.5 species, but did not explain all of the model variation.

Thatcher, T.L.; Lunden, M.; Revzan, K.; Sextro, R.G.; Brown, N. "Experimental investigation of the effect of changes in house environment on the indoor concentration of particles of outdoor origin within a residence." 2002. LBNL-51002.

Abstract. Abstract not available.

Thatcher, T.L.; Lai, A.C.K.; Moreno-Jackson, R.; Sextro, R.G.; Nazaroff, W.W. "Effects of Room Furnishings and Air Speed on Particle Deposition Rates Indoors." Atmospheric Environment, Volume 36, Pages 1811-1819. 2002. LBNL-48414.

Abstract. No Abstract available

Sippola, M.R.; Nazaroff, W.W. "Modeling Particle Deposition In Ventilation Ducts." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 515-520, Indoor Air 2002, Santa Cruz, CA. 2002.

Abstract. This paper describes predictions from two models of fractional particle loss in four typical HVAC duct runs. One model is a state-of-the-art Eulerian formulation; the second is based on empirical fits to experimental particle deposition data collected in a laboratory. The experiments are briefly described and sample results are presented. The Eulerian model only predicts deposition from fully developed turbulence, while the empirical model can be applied to duct bends and developing turbulence as well. The models predict almost no losses for particles smaller than 1 μm and nearly complete loss of particles larger than 40 μm in all duct runs. The empirical model suggests that particle loss in ventilation ducts is dominated by gravitational settling to the floor of horizontal ducts, and by deposition to zones where turbulent flow is undeveloped, such as in bends and in duct sections immediately after bends.

Siegel, J.A.; Nazaroff, W.W. "Modeling Particle Deposition on HVAC Heat Exchangers." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 521-526, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49339 .

Abstract. Fouling of fin-and-tube heat exchangers by particle deposition leads to diminished effectiveness in supplying ventilation and air conditioning. This paper explores mechanisms that cause particle deposition on heat exchanger surfaces. We present a model that accounts for impaction, diffusion, gravitational settling, and turbulence. Simulation results suggest that some submicron particles deposit in the heat exchanger core, but do not cause significant performance impacts. Particles between 1 and 10 μm deposit with probabilities ranging from 1 – 20 % with fin edge impaction representing the dominant mechanism. Particles larger than 10 μm deposit by impaction on refrigerant tubes, gravitational settling on fin corrugations, and mechanisms associated with turbulent airflow. The model results agree reasonably well with experimental data, but the deposition of larger particles at high velocities is underpredicted. Geometric factors, such as discontinuities in the fins, are hypothesized to be responsible for the discrepancy.

Riley, W.J.; T.E. McKone; A.C.K. Lai; W.W. Nazaroff. "Indoor particulate matter of outdoor origin: importance of size-dependent removal mechanisms." Environmental Science & Technology, Volume 36, Pages 200-207. 2002. LBNL-47437 .

Abstract. Adverse human health effects have been observed to correlate with levels of outdoor particulate matter (PM), even though most human exposure to PM of outdoor origin occurs indoors. In this study, we apply a model and empirical data to explore the indoor PM levels of outdoor origin for two major building types: offices and residences. Typical ventilation rates for each building

type are obtained from the literature. Published data are combined with theoretical analyses to develop representative particle penetration coefficients, deposition loss rates, and ventilation-system filter efficiencies for a broad particle size range (i.e., 0.001-10 um). We apply archetypal outdoor number, surface area, and mass PM size distributions for both urban and rural airsheds. We also use data on mass-weighted size distributions for specific chemical constituents of PM: sulfate and elemental carbon. Predictions of the size-resolved indoor proportion of outdoor particles (IPOP) for various conditions and ambient particle distributions are then computed. The IPOP depends strongly on the ambient particle size distribution, building type and operational parameters, and PM metric. We conclude that an accurate determination of exposure to particles of ambient origin requires explicit consideration of how removal processes in buildings vary with particle size.

Mora, L.; A.J. Gadgil. "Theoretical study of pollutant mixing in rooms induced by occupancy." Proceedings of the Room Vent 2002 Conference, Copenhagen, Denmark, Pages 257-260. 2002. LBNL-49730 .

Abstract. Airflow and pollutant transport models are commonly based on the approximation that air is instantaneously well mixed in a zone. In many circumstances this approximation is unsatisfactory. We present a semi-empirical model to predict the time required by a pollutant to disperse in a room, owing to the effects of room occupancy (room mixing induced by thermal plumes, stirring by people walking about and breathing). We base our estimates on previous experimental work correlating the mixing tome for a pollutamt pulse released in a room to the mechanical energy supplied to the room air. Our results suggests that people moving about in a room can induce rapid mixing. For example, the mixing timeresulting from a person walking at 1.4 m/s in a 30 m^3 room is predicted to be about 4 minutes . In this case, the assumption that air is well mixed could be reasonable.

Lunden, M.M.; Thatcher, T.L.; Littlejohn, D.; Fischer, M.L.; Hering, S.V.; Sextro, R.G.; Brown, N.J. "The Transformation Of Outdoor Ammonium Nitrate Aerosols In The Indoor Environment." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 5, Pages 74-79, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-50158 .

Abstract. Recent studies associate particulate air pollution with adverse health effects; however, the exposure to indoor particles of outdoor origin is not well characterized, particularly for individual chemical species. In response to this, a field study in an unoccupied, single-story residence in Clovis, California has been conducted. Real-time particle monitors were used both outdoors and indoors to quantify PM2.5 nitrate, sulfate, and carbon. The results show that reduced indoor sulfate and carbon levels are primarily due to deposition and penetration losses. However, measured indoor ammonium nitrate levels were often observed to be at significantly lower levels than expected based solely on penetration and deposition losses. The additional reduction appears to be due to the transformation of ammonium nitrate into ammonia and nitric acid indoors, which are subsequently lost by deposition and sorption to indoor surfaces. The size of the effect is dependent upon factors such as temperature, relative humidity, and ventilation rate.

Liu, D.L.; Nazaroff, W.W. "Particle Penetration Through Windows." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 862-867, Indoor Air 2002, Santa Cruz, CA. 2002. No LBNL number.

Abstract. This study aims to characterize the fractional penetration of airborne particles through windows, one of the important sites of air leakage through building envelopes. Two aluminum windows were evaluated, one with weatherstripping and one without. For each experiment, a finished window was mounted and sealed in a plywood panel that separated two well-mixed compartments. A small pressure difference was established between the compartments to induce a constant rate of airflow through leakage paths in the window. Particles were injected into one chamber and their concentrations were measured in both chambers. Two methods were employed to evaluate the size-resolved particle penetration: a steady-state method and a dynamic, concentration growth method. The results indicate that airborne particles of 0.2 to 3 ?m penetrate through both test windows fairly effectively, while significant particle losses are observed for particles smaller and larger than this range.

Hering, S.V.; Lunden, M.M.; Kirchstetter, T.W.; Thatcher, T.L.; Revzan, K.L.; Sextro, R.G.; Brown, N.J.; Watson, J.; Chow, J. "Indoor, Outdoor And Regional Profiles Of Pm2.5 Sulfate, Nitrate And Carbon." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 874-879, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49980 .

Abstract. Fine particle concentrations were measured simultaneously at three locations: a regional monitoring site in Fresno, California, a backyard of an unoccupied residence in Clovis, California located 6 km northeast of the regional site; and indoors at the same residence. Measurements included 10-min determination of PM2.5 nitrate, sulfate and carbon using an automated collection and vaporization system, and black carbon measured by light attenuation through a filter deposit. Specific outdoor PM2.5 constituents were compared to assess the appropriateness of using regional data to model indoor concentrations from outdoor sources. The outdoor data show that, in general, the regional results provide a good representation of the concentrations seen at the building exterior. The indoor concentrations showed considerable attenuation as well as a broadening and time-lag for the concentration peaks. The concentration reduction was the largest for PM2.5 nitrate, which appears to undergo phase changes in addition to indoor deposition and penetration losses.

Fisk, WJ; Faulkner, D; Palonen, J; Seppänen, O. "Performance and cost of particle air filtration technologies." Indoor Air, Volume 12, Pages 223-234. 2002. LBNL-47833.

Abstract. This paper predicts the reductions in the indoor mass concentrations of particles attainable from use of filters in building supply airstreams and also from use of stand-alone fan-filter units. Filters with a wide efficiency range are considered. Predicted concentration reductions are provided for indoor-generated particles containing dust mite and cat allergen, for environmental tobacco smoke particles, and for outdoor- air fine mode particles. Additionally, this paper uses a simple model and available data to estimate the energy and total costs of the filtration options. Predicted reductions in cat and dust-mite allergen concentrations range from 20% to 80%. To obtain substantial, e.g., 50%, reductions in indoor concentrations of these allergens, the rate of airflow through the filter must be at least a few indoor volumes per hour. Increasing filter efficiencies above approximately ASHRAE Dust Spot 65% does not significantly reduce predicted indoor concentrations of these allergens. For environmental tobacco smoke particles and outdoor fine mode particles, calculations indicate that relatively large, e.g., 80%, decreases in indoor concentrations are attainable with practical filter efficiencies and flow rates. Increasing the filter efficiency above ASHRAE 85% results in only modest predicted incremental decreases in indoor concentration. Energy costs and total costs can be similar for filtration using filters with a wide range of efficiency ratings. Total estimated filtration costs of approximately $0.70 to $1.80 per person per month are insignificant relative to salaries, rent, or health insurance costs.

Fischer, M.L.; Lunden, M.M.; Thatcher, T.L.; Littlejohn, D.; Kirchstetter, T.W.; Hering, S.V.; Sextro, R.G.; Brown, N.J. "Building a predictive model of indoor concentrations of outdoor PM-2.5 for a residential research house in Clovis, California." 2002. LBNL-51001.

Abstract. The prevalence of relocatable classrooms (RCs) at schools is rising due to federal and state initiatives to reduce K-3 class size, and limited capital resources. Concerns regarding inadequate ventilation and indoor air and environmental quality (IEQ) in RCs have been raised. Adequate ventilation is an important link between improved IEQ and energy efficiency for schools. Since students and teachers spend the majority of a 7-8 hour school day inside classrooms, indoor contaminant concentrations are assumed to drive personal school-day exposures. We conducted a demonstration project in new relocatable classrooms (RCs) during the 2001-02 school year to address these issues. Four new 24' x 40' (960 ft2) RCs were constructed and sited in pairs at an elementary school campus in each of two participant school districts (SD) in Northern California. Each RC was equipped with two heating, ventilation, and air conditioning (HVAC) systems, one per module. The two HVAC systems were a standard heat pump with intermittent 25-50% outdoor air ventilation and an energy-efficient advanced system, based on indirect-direct evaporative cooling with an integrated natural gas-fired hydronic heating loop and improved particle filtration, providing continuous 100% outdoor air ventilation at = 15 ft3 min-1 occupant-1. Alternate carpets, wall panels, and ceiling panels were installed in two classrooms – one in each pair – based on the results of a laboratory

study of VOC emissions from standard and alternate materials. Numerous IEQ and outdoor air quality and meteorological parameters were measured either continuously over the school year or as integrated school day samples during the fall cooling and winter heating seasons. Details of the RC designs, the field monitoring methodology including handling, storage, transport and management of chemical samples and data, and analyses to be conducted are presented.

Fischer, M.L.; Lunden, M.M.; Thatcher, T.L.; Sextro, R.G.; Brown, N.J. "Predicting Indoor PM2.5 Of Outdoor Origin: Testing a transient size-resolved Model Using Intensive Measurements From A Residence." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 152-157, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49615.

Abstract. We report tests of a model for indoor PM2.5 of outdoor origin that incorporates physical mechanisms for time dependent transport, and size dependent penetration and deposition. This work was performed using information obtained from an intensive study of a house near Fresno, CA, USA. During the multi-week study covering two seasons, we measured particles in both indoor and outdoor air, with high temporal, chemical, and size resolution, and other variables that also affect transport and fate. Results suggest that 1) the model captures a significant fraction of the variation in meteorologically forced air infiltration rate, 2) the predicted indoor/outdoor PM2.5 ratio is not consistent with the measured ratio unless a large (unphysical) deposition rate ¿ 2 hr-1 is assumed, and 3) the differences between model and measurement in indoor PM2.5 are likely due to loss of volatile ammonium-nitrate aerosol. We conclude that nitrate particle volitization must be included in the model formulation.

Thatcher, T.L.; McKone, T. E.; Fisk, W. J.; Sohn, M.D.; Delp, W.W.; Riley, W.J.; Sextro, R. G. "Factors Affecting the Concentration of Outdoor Particles Indoors (COPI): Identification of Data Needs and Existing Data." 2001. LBNL-49321 .

Siegel, Jeffrey. "Fouling of HVAC fin and tube heat exchangers." 2001. LBNL-47668 .

Abstract. Fin and tube heat exchangers are used widely in residential, commercial and industrial HVAC applications. Invariably, indoor and outdoor air contaminants foul these heat exchangers. This fouling can cause decreased capacity and efficiency of the HVAC equipment as well as indoor air quality problems related to microbiological growth. This paper describes laboratory studies to investigate the mechanisms that cause fouling. The laboratory experiments involve subjecting a 4.7 fins/cm (12 fins/inch) fin and tube heat exchanger to an air stream that contains monodisperse particles. Air velocities ranging from 1.5 – 5.2 m/s (295 ft/min – 1024 ft/min) and particle sizes from 1 – 8.6 μm are used. The measured fraction of particles that deposit as well as information about the location of the deposited material indicate that particles greater than about 1 μm contribute to fouling. These experimental results are used to validate a model that describes the relative importance of several deposition mechanisms including impaction, Brownian diffusion, turbophoresis and gravitational settling. The analysis is extended to apply to different fin spacings and particle sizes typical of those found in indoor air.

Siegel, J.A.; Walker, I.S. "Deposition of biological aerosols on HVAC heat exchangers." 2001. LBNL-47669 .

Abstract. Many biologically active materials are transported as bioaerosols 1-10 μm in diameter. These particles can deposit on cooling and heating coils and lead to serious indoor air quality problems. This paper investigates several of the mechanisms that lead to aerosol deposition on fin and tube heat exchangers. A model has been developed that incorporates the effects of several deposition mechanisms, including impaction, Brownian and turbulent diffusion, turbophoresis, thermophoresis, diffusiophoresis, and gravitational settling. The model is applied to a typical range of air velocities that are found in commercial and residential HVAC systems 1 – 6 m/s (200 – 1200 ft/min), particle diameters from 1 – 8 μm, and fin spacings from 3.2 – 7.9 fins/cm (8 – 16 fins/inch or FPI). The results from the model are compared to results from an experimental apparatus that directly measures deposition on a 4.7 fins/cm (12 FPI) coil. The model agrees reasonably well with this measured data and suggests that cooling coils are an important sink for biological aerosols and consequently a potential source of indoor air quality problems.

Lunden, M.M.; Thatcher, T.L.; Littlejohn, D.; Fischer, M.L.; Kirchstetter, T.W.; Brown, N.J.; Hering, S.; Stolzenburg, M. "Building a predictive model of indoor concentrations of outdoor PM-2.5 in homes." 2001. LBNL-48929.

Lorenzetti, D.M. "Assessing Multizone Airflow Software." 2001. LBNL-47653 .

Abstract. Multizone models form the basis of most computer simulations of airflow and pollutant transport in buildings. In order to promote computational effciency, some multizone simulation programs, such as COMIS and CONTAM, restrict the form that their flow models may take. While these tools allow scientists and engineers to explore a wide range of building airflow problems, increasingly their use has led to new questions not answerable by the current generation of programs. This paper, directed at software developers working on the next generation of building airflow models, identifies structural aspects of COMIS and related programs that prevent them from easily incorporating desirable new airflow models. The paper also suggests criteria for evaluating alternate simulation environments for future modeling efforts.

Carrie, F.R.; Modera, M.P. "Experimental investigation of aerosol deposition on slot-and joint-type leaks." Journal of Aerosol Science, Volume 33, Pages 1447-1462. 2001. LBNL-48774 .

Tsai, F.; Apte, M.G.; Daisey, J. "An Exploratory Analysis of the Relationship between Mortality and the Chemical Composition of Airborne Particulate Matter." Inhalation Toxicology, Volume 12, Pages 121-135. 2000. LBNL-43583 .

Thatcher, T.L.; Lai, A.C.K.; Moreno-Jackson, R.; Sextro, R.G.; Nazaroff, W.W. "Experimental Determination Of Size Resolved Particle Deposition Rates As A Function Of Room Furnishing And Room Air Velocity, Section 11PC." Proceedings of the 19th Annual American Association of Aerosol Research, St. Louis, MO, Pages 332, The American Association of Aerosol Research, Cincinnati, OH. 2000.

Thatcher, T.L.; Lunden, M.M.; Fischer, M.L.; Fine, J.D.; Kirchstetter, T.W.; Hering, S.; Sextro, R.G.; Brown, N.J. "A Concentration Rebound Method For Measuring Particle Penetration Into A Residence, Section 12A1." Proceedings of the 19th Annual American Association for Aerosol Research, St. Louis, MO, The American Association for Aerosol Research, Cincinnati, OH. 2000.

Lunden, M.M.; Fischer, M.L.; Fine, J.D.; Thatcher, T.L.; Kirchstetter, T.W.; Hering, S.; Sextro, R.G.; Brown, N. J. "A Predictive Model Of Indoor Concentrations Of Outdoor Pm-2.5 In Homes." Proceedings of the 19th Annual American Association of Aerosol Research, St. Louis, MO, Volume Session 1A, Pages 5, The American Association for Aerosol Research, Cincinnati, OH. 2000.

Litvak, A.; Gadgil, A.J.; Fisk, W.J. "Hygroscopic Fine Mode Particle Deposition on Electronic Circuits and Resulting Degradation of Circuit Performance: An Experimental Study." Indoor Air, Volume 10, Pages 47-56. 2000. LBNL-41315.

Fisk, W.J.; Faulkner D.; Sullivan, D.; Mendell, M.J. "Particle concentrations and sizes with normal and high efficiency filtration in a sealed air-conditioned office building." Aerosol Science & Technology, Volume 32, Pages 527-544. 2000. LBNL-43835.

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Sohn, M.D.; A. Lai; B.V. Smith; R.G. Sextro; H.E. Feustel; W.W. Nazaroff. "Modeling aerosol behavior in multizone indoor environments." Proceedings of the Indoor Air '99, Edinburgh, Scotland, Volume 4, Pages 785-790, Construction Research Communications, Ltd., London. 1999. LBNL-42708.

Abstract. A publicly available aerosol dynamics model, MIAQ4, is coupled to a widely used multizone air flow and transport model, COMIS, to better understand and quantify the behavior of

particles in indoor environments. MIAQ4 simulates the evolution of a size and chemically resolved particle distribution, including the effects of direct indoor emission, ventilation, filtration, deposition, and coagulation. COMIS predicts interzonal air-exchange rates based on pressure gradients (due to wind, buoyancy, and HVAC operation) and leaks between the zones and with the outside. The capabilities of the coupled system are demonstrated by predicting the transport of particles from two sources in a residence: environmental tobacco smoke (ETS) and particles generated from cooking. For ETS, MIAQ4 predicts particle size distributions that are similar to the emission source profile because ETS particles, concentrated in the size range 0.1 – 1 ?m, are transformed by coagulation and deposition slowly compared with the rates of transport. For cooking, MIAQ4 predicts that the larger-sized particles will settle rapidly, causing a shift in size distribution as emissions are transported to other rooms.

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2. Commercial Building and Classroom Energy and Environmental Quality

2.1. Energy Retrofits and Diagnostics

Rainer, L.; Hoeschele, M.; Apte, M.G.; Shendell, D.G.; Fisk, W.J. "Energy savings estimates and cost benefit calculations for high performance relocatable classrooms." 2004. LBNL-54230 .

Abstract. This report addresses the results of detailed monitoring completed under Program Element 6 of Lawrence Berkeley National Laboratory's High Performance Commercial Building Systems (HPCBS) PIER program. The purpose of the Energy Simulations and Projected State-Wide Energy Savings project is to develop reasonable energy performance and cost models for high performance relocatable classrooms (RCs) across California climates. A key objective of the energy monitoring was to validate DOE2 simulations for comparison to initial DOE2 performance projections. The validated DOE2 model was then used to develop statewide savings projections by modeling base case and high performance RC operation in the 16 California climate zones. The HPCBS energy efficient RC design is based upon earlier work by Davis Energy Group with Pacific Gas and Electric Company (PG&E), which culminated in the PG&E Premium Efficient Relocatable Classroom (PERC) program (DEG 1997). The envelope energy efficiency measures selected for the HPCBS project are similar to the PERC Package 1 except the HPCBS package substitutes a white ("Cool Roof") coating for the radiant barrier in the attic space. In addition to the standard wall-mount heat pump system (HPAC), the HPCBS RCs utilize an advanced hybrid system combining an Indirect/Direct Evaporative Cooler (IDEC), which provides two-stage evaporative cooling, and an instantaneous gas-fired heater and hydronic coil for heating. Simulations described in this report add upon those conducted in program year one, with the benefit of data collected during the energy and indoor air and environmental quality (IEQ) field monitoring. Data from the field studies have been used to improve model inputs. The revised DOE2 analyses presented here provide an improved assessment of statewide energy performance for both base case and high performance RCs. Since the initiation of this project a new revision of the California Title 24 Building Standards has begun (scheduled for release in 2005). As part of this process, RCs were examined and new code enforcement procedures were developed which will result in new RCs having envelope energy features very close to the HPCBS design. Table 1 summarizes key energy features of the HPCBS RC package. Additional background information on the construction details and assumed operating characteristics of RCs, as well as full-year DOE2 performance projections, can be found in the 2001 project report entitled Relocatable Classroom DOE2 Analysis Report, (Apte et al 2001, Shendell et al 2002)

Diamond, R. "An R&D guide and multiyear plan for improving energy use in existing commercial buildings." 2004. LBNL-56173.

Diamond, R.; Moezzi, M. "Changing trends: A brief history of the U.S. household consumption of energy, water, food, beverages and tobacco." Submitted to 2004 ACEEE Summer Study, Pacific Grove, CA, American Council for an Energy Efficient Economy, Washington, DC. 2004. LBNL-55011 .

Abstract. Can an historic analysis of consumption patterns of different commodities in the U.S. shed light on the consumption of energy? Can a review of past policies to reduce or change consumption patterns provide insight or guidance in developing new policies for reducing energy use? In order to better understand energy conservation policies, we take a brief look at the history in the US of consumption and curtailment of different commodities, including energy, raw materials, water, beverages and tobacco. Per capita consumption of all of these commodities has fluctuated over the past 100 years. With few exceptions, policies to reduce their consumption, e.g., prohibition, exhortation, regulation, taxation, have had little effect on consumption. Periods of curtailment, e.g., wartime, natural disasters and other shortages, have led to reductions in consumption, which were generally short lived. In some cases, reductions in consumption resulted in less service. In other cases, reduction in consumption led to changes in the services provided. By reviewing the history of consumption and curtailment we identify strategies that have the potential for promoting the long-term conservation of energy.

Apte, M G.; Hodgson, A.T; Shendel, D.G.; Rainer, L.I.; Hoeschele, M.A. "Designing Building Systems to Save Energy and Improve Indoor Environments: A Practical Demonstration." Submitted to 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy, Washington, DC. 2004. LBNL-54859 .

Abstract. Building design concepts that focus on energy efficiency may conflict with those intended to provide excellent indoor environmental quality (IEQ). Careful selection of a heating, ventilating, and air-conditioning (HVAC) system, and low-emission interior finish materials, can result in winwin designs that minimize tradeoffs between energy and IEQ. We demonstrated energy and IEQ benefits in four new relocatable classrooms (RCs) monitored in two climate regions of California for one year. We used a case-crossover experimental design to compare energy and IEQ characteristics of a hybrid HVAC system that provides continuous ventilation (indirect-direct evaporative cooler with high-efficiency hydronic gas heat) to a standard heat pump system. Additionally, we explored the IEQ benefits of measurement-based selection of interior finish materials with low emissions of health-relevant volatile organic compounds (VOCs) including formaldehyde. Monitored data were used to calibrate DOE-2 models that simulated California-wide energy saving potential of RCs employing energy efficient building components including the hybrid HVAC system. IEQ monitoring results from our field investigation indicated that VOC concentration reductions, typically 50% or more, were achieved through improved ventilation while simultaneously average cooling and heating energy costs were reduced by 50% and 30%, respectively. Incremental annual California-wide energy impacts from installation of hybrid HVAC systems in 4,000 new RCs were projected to be: 5,975 MWh of electricity savings; 23.8 MW winter and 13.1 MW summer peak electric load reduction; 1,025 MBtu natural gas consumption from switch to gas heating; 50,931 MBtu source energy reduction; and a combined school district annual operating cost reduction of $880,900.

Fisk, W.J.; Price, P.N.; Faulkner, D.; Sullivan, D.P.; DiBartolomeo, D.L.; Federspiel, C.; Liu, G.; Lahiff, M. "Worker productivity and ventilation rate in a call center: Analyses of time-series data for a group of registered nurses." 2003. LBNL-53785 .

Abstract. We investigated the relationship of ventilation rates with the performance of advice nurses working in a call center. Ventilation rates were manipulated; temperatures, humidities, and CO2 concentrations were monitored; and worker performance data, with 30-minute resolution, were collected. Multivariate linear regression was used to investigate the association of worker performance with indoor minus outdoor CO2 concentration (which increases with decreasing ventilation rate per worker) and with building ventilation rate. Results suggest that the effect of ventilation rate on worker performance in this call center was very small (probably less than 1%) or nil, over most of the range of ventilation rate (roughly 12 L s-1 to 48 L s-1 per person). However, there is some evidence of worker performance improvements of 2% or more when the indoor CO2 concentration exceeded the outdoor concentration by less than 75 ppm.[1067]

Diamond, Rick. 2003. "A lifestyle-based scenario for U.S. buildings: Implications for energy us." Energy Policy, Volume 31, Pages 1205-1211. 2003. LBNL-50969 .

Abstract. Can lifestyle-based scenarios provide insight into the nature of energy use in our future buildings? Participants in a design charrette brainstormed ideas about the future of US homes and workplaces. The teams started from several descriptions of daily lifestyles, and developed specific building characteristics as the place settings for these narratives. In addition to characterizing the physical environment, the teams also identified the forces that would be influential in making these changes. Further reflection was made on the possible unintended consequences of these changes. The energy implications of these changes were characterized with respect to magnitude and direction. While acknowledging the speculative nature of the exercise, the rationale was to broaden the discussion on future energy use by looking at future scenarios in the context of everyday life.

Apte, M G.; Hodgson, A.; Shendel, D.G.; Dibartolomeo, D.; Hotchi, T.; Lee, S-M; Liff, S.; Rainer, L.; Sullivan, D; Fisk, W.J. "Simultaneous Improvements in Relocatable Classrooms." ASHRAE IAQ Applications, Pages 7-10. 2003. LBNL-54870 .

Apte, M.G.; Hodgson, A.T.; Shendell, D.G.; Dibartolomeo, D.; Hotchi, T.; Lee, S.M.; Liff, S.M.; Rainer, L.I.; Sullivan, D.P.; Fisk, W.J.. "Simultaneous Energy Savings and IEQ Improvements in Relocatable Classrooms." 2003. LBNL-52690 .

Abstract. Relocatable classrooms (RCs) are commonly used by school districts with changing demographics and enrollment sizes. We designed and constructed four energy-efficient RCs for this study to demonstrate technologies with the potential to simultaneously improve energy efficiency and indoor environmental quality (IEQ). Two were installed at each of two school districts, and energy use and IEQ parameters were monitored during occupancy. Two RCs (one per school) were finished with materials selected for reduced emissions of toxic and odorous volatile organic compounds (VOCs). Each had two HVAC systems, operated on alternate weeks, consisting of a standard heat-pump system and an indirect-direct evaporative cooling (IDEC) system with gas-fired hydronic heating. The IDEC system provides continuous outside air ventilation at "15 CFM (7.5 L s-1) person-1, efficient particle filtration while using significantly less energy for cooling. School year long measurements included: carbon dioxide (CO2), particles, VOCs, temperature, humidity, thermal comfort, noise, meteorology, and energy use. IEQ monitoring results indicate that important ventilation-relevant indoor CO2 and health-relevant VOC concentration reductions were achieved while average cooling and heating energy costs were simultaneously reduced by 50% and 30%, respectively.

Diamond, R.C.; M. Moezzi. "Becoming allies: Combining social science and technological perspectives to improve energy research and policy making." Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 4, Pages 89-104, American Council for an Energy Efficient Economy, Washington, DC. 2002. LBNL-50704 .

Abstract. Within the energy research community, social sciences tends to be viewed fairly narrowly, often as simply a marketing tool to change the behavior of consumers and decision makers, and to "attack market barriers." As we see it, social sciences, which draws on sociology, psychology, political science, business administration, and other academic disciplines, is capable of far more. A social science perspective can re- align questions in ways that can lead to the development of technologies and technology policy that are much stronger and potentially more successful than they would be otherwise. In most energy policies governing commercial buildings, the prevailing R&D directives are firmly rooted in a technology framework, one that is generally more quantitative and evaluative than that fostered by the social sciences. To illustrate how social science thinking would approach the goal of achieving high energy performance in the commercial building sector, we focus on the U.S. Department of Energy's Roadmap for commercial buildings (DOE 2000) as a starting point. By "deconstructing" the four strategies provided by the Roadmap, we set the stage for proposing a closer partnership between advocates of technology-based and social science-based approaches.

Salsbury, T.I.; Diamond, R.C. "Fault Detection in HVAC Systems Using Model-Based Feedforward Control." Energy & Buildings, Volume 33, Pages 403-415. 2001. LBNL-45867.

Piette, M.A.; J.H. Eto; I.S. Walker; S. Selkowitz; C.P. Wray; B. Nordman; A. Meier; P. Haves; R. Diamond; J. Harris; M. Moezzi; C. Payne; J. Koomey. "Demand-Responsive and Efficient Building Systems as a Resource for Electricity Reliability." 2001. LBNL-47942.

Salsbury, T.I.; Diamond, R.C. "Implementation and testing of a fault detection software tool for improving control system performance in a large commercial building." Proceedings of the ACEEE 2000 Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 7, Pages 147-158, American Council for an Energy Efficient Economy, Washington, DC. 2000. LBNL-45863.

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Diamond, R.C.; Salsbury, T.; Bell, G.; Huang, Y.J.; Sezgen, O.; Mazzuchi, R.; Roberger, J. "Phillip Burton Federal Building: EMCS Retrofit Analysis." 1999. LBNL-43256.

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Warner, J.; Sartor, D.; Diamond, R. "Tenant Guidelines for Energy-Efficient Renovation of Buildings at the Presidio of San Francisco." 1997. PUB-798.

Diamond,R.C. "Multifamily ventilation." Home Energy, Volume 14. 1997.

Sartor, D. A.; Diamond, R. C.; Walker, A.; Giller, M.; Brown, K.; Crawley, A. S. "Designing an Environmental Showcase: The San Francisco Presidio." Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 5, Pages 209-218, American Council for an Energy Efficient Economy, Washington, DC. 1996.

Hammon, R.W.; Modera M.P. "Improving the Energy Efficiency of Air Distribution Systems in New California Homes." Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 2, Pages 85-95, American Council for an Energy Efficient Economy, Washington, DC. 1996. LBL-31636.

Diamond, R.C.; Remus, J.; Vincent, B. "User Satisfaction with Innovative Cooling Retrofits in Sacramento Public Housing." Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 8, Pages 21, American Council for an Energy Efficient Economy, Washington, DC. 1996.

DeCicco, J.; Diamond, R. C.; Nolden, S.; Wilson, T. "Improving Energy Efficiency in Apartment Buildings." 1996.

Busch, J.; Diamond, R. C. "Does the Feebate Approach to A/E Compensation Lead to and Energy-Efficient Building?." Proceedings of the 4th National Energy-Efficient New Construction Conference, Vancouver, BC, ADM Associates, Sacramento, CA. 1996.

Tzonis, A.; Lefaivre, L.; Diamond, R. "Architecture in North America since 1960." 1995.

Piette, M. A.; Nordman, B.; Buen, O. D.; Diamond, R. C. "Findings from a Low-Energy, New Commercial-Buildings Research and Demonstration Project." Energy, Volume 20, Pages 471-482. 1995. LBL-36506.

Diamond, R.C. "An Overview of the Multifamily Sector." Home Energy, Volume 12, Pages 22-25. 1995.

Diamond, R.C.; Feustel, H.E.; Dickerhoff, D.J. "Energy and Ventilation Research in Highrise Apartments: The Chelsea Public Housing Study." Proceedings of the 15th AIVC Annual Conference, Palm Springs, CA, Air Infiltration and Ventilation Centre, Coventry, Great Britain. 1995.

2.2. Health and Productivity Effects

Shendell, D.G; Prill,R.; Fisk, W.J.; Apte, M.G.; Blake, D.; Faulkner, D. "Associations between classroom CO2 concentrations and student attendance in Washington and Idaho." Accepted for publication in Indoor Air 2004. 2004. LBNL-54413 .

Abstract. Student attendance in American public schools is a critical factor in securing limited operational funding. Student and teacher attendance influence academic performance. Limited data exist on indoor air and environmental quality (IEQ) in schools, and how IEQ affects attendance, health, or performance. This study explored the association of student absence with measures of indoor minus outdoor carbon dioxide concentration (dCO2). Absence and dCO2 data were collected from 409 traditional and 25 portable classrooms from 22 schools located in six school districts in the states of Washington and Idaho. Study classrooms had individual heating, ventilation, and air conditioning (HVAC) systems, except two classrooms without mechanical ventilation. Classroom attributes, student attendance and school-level ethnicity, gender, and socioeconomic status (SES) were included in multivariate modeling. Forty-five percent of classrooms studied had short-term indoor CO2 concentrations above 1000 parts-per-million (ppm). A 1000 ppm increase in dCO2 was associated (p ¡ 0.05) with a 0.5% to 0.9% decrease in annual average daily attendance (ADA), corresponding to a relative 10% to 20% increase in student absence. Annual ADA was 2% higher (p ¡ 0.0001) in traditional than in portable classrooms.

Seppanen, O.; Fisk, W.J. "Summary of human responses to ventilation." Submitted to Special Issue of Indoor Air. 2004. LBNL-55748 .

Abstract. The effects of ventilation on indoor air quality and health is a complex issue. It is known that ventilation is necessary to remove indoor generated pollutants from indoor air or dilute their concentration to acceptable levels. But, as the limit values of all pollutants are not known, the exact determination of required ventilation rates based on pollutant concentrations and associated risks is seldom possible. The selection of ventilation rates has to be based also on epidemiological research (e.g. Seppänen et al., 1999), laboratory and field experiments (e.g. CEN 1996, Wargocki et al., 2002a) and experience (e.g. ECA 2003).

Ventilation may also have harmful effects on indoor air quality and climate if not properly designed, installed, maintained and operated as summarised by Seppänen (2003). Ventilation may bring indoors harmful substances that deteriorate the indoor environment. Ventilation also affects air and moisture flow through the the building envelope and may lead to moisture problems that deteriorate the structures of the building. Ventilation changes the pressure differences over the structures of building and may cause or prevent the infiltration of pollutants from structures or adjacent spaces. Ventilation is also in many cases used to control the thermal environment or humidity in buildings.

Ventilation can be implemented with various methods which may also affect health (e.g. Seppänen and Fisk, 2002, Wargocki et al., 2002a). In non residential buildings and hot climates, ventilation is often integrated with air-conditioning which makes the operation of ventilation system more complex. As ventilation is used for many purposes its health effects are also various and complex. This paper summarises the current knowledge on positive and negative effects of ventilation on health and other human responses. The focus of the paper is on office-type working environment and residential buildings. In the industrial premises the problems of air quality are usually more complex and case specific. They are subject to occupational safety legislation and not discussed here.

Seppanen, O.; Fisk, W.J. "A model to estimate the cost effectiveness of indoor environment improvements in office work." Submitted to ASHRAE Transactions. 2004. LBNL-55447 .

Abstract. Deteriorated indoor climate is commonly related to increases in sick building syndrome symptoms, respiratory illnesses, sick leave, reduced comfort and losses in productivity. The cost of deteriorated indoor climate for the society is high. Some calculations show that the cost is higher than the heating energy costs of the same buildings. Also building-level calculations have shown that many measures taken to improve indoor air quality and climate are cost-effective when the potential monetary savings resulting from an improved indoor climate are included as benefits gained. As an initial step towards systemizing these building level calculations we have developed a conceptual model to estimate the cost-effectiveness of various measures. The model shows the links between the improvements in the indoor environment and the following potential financial benefits: reduced medical care cost, reduced sick leave, better performance of work, lower turn over of employees, and lower cost of building maintenance due to fewer complaints about indoor air quality and climate. The pathways to these potential benefits from changes in building technology and practices go via several human responses to the indoor environment such as infectious diseases, allergies and asthma, sick building syndrome symptoms, perceived air quality, and thermal environment. The model also includes the annual cost of investments, operation costs, and cost savings of improved indoor climate. The conceptual model illustrates how various factors are linked to each other. SBS symptoms are probably the most commonly assessed health responses in IEQ studies and have been linked to several characteristics of buildings and IEQ. While the available evidence indicates that SBS symptoms can affect these outcomes and sugpects that such a linkage exists, at present we can not quantify the relationships sufficiently for cost-benefit modeling. New research and analyses of existing data to quantify the financial importance of SBS symptoms would enable more widespread consideration of the effects of IEQ in cost benefit calculations.

Seppanen, O.; Fisk, W.J. "Control of temperature for health and productivity in offices." Submitted to

ASHRAE Transactions. 2004. LBNL-55448 .

Abstract. Indoor temperature is one of the fundamental characteristics of the indoor environment. It can be controlled with different accuracy depending on the building and its HVAC system. The purpose of this study was to evaluate the potential benefits of improved temperature control, and apply the information for a cost-benefit analyses. The indoor temperature affects several human responses, including thermal comfort, perceived air quality, sick building syndrome symptoms and performance in work. In this study we focused on the effects of temperature on performance in work. We collected and analyzed the literature relating the performance in work and temperature. The results of multiple studies are relatively consistent and show an average relationship of 2% decrement in work performance per degree oC when the temperature is above 25oC. Less data were available on the performance in low temperatures. However, studies show a strong effect on manual tasks with temperatures below thermal neutrality as soon as the temperature of hands decreased due to control of blood flow. When the estimated productivity decrement from elevated temperetures was applied to data from a study of night-time ventilative cooling, the estimated value of productivty improvements were 32 to 120 times greater than the cost of energy to run fans during the night.

Kim, J.J.; Svetlana, S.; Lipsett, M.; Singer, B.C.; Hodgson, A.; Ostro, B. "Traffic-related Air Pollution near Busy Road: The East Bay Children's Respiratory Health Study." American Journal of Respiratory and Critical Care Medicine, Volume 170, Pages 520526. 2004. LBNL-55586 .

Abstract. Recent studies, primarily in Europe, have reported associations between respiratory symptoms and residential proximity to traffic; however, few have measured traffic pollutants or provided information about local air quality. We conducted a school-based, crosssectional study in the San Francisco Bay Area in 2001. Information on current bronchitis symptoms and asthma, home environment, and demographics was obtained by parental questionnaire (n = 1,109). Concentrations of traffic pollutants (particulate matter, black carbon, total nitrogen oxides [NOX], and nitrogen dioxide [NO2]) were measured at 10 school sites during several seasons. Although pollutant concentrations were relatively low, we observed differences in concentrations between schools nearby versus those more distant (or upwind) from major roads. Using a two-stage multiple-logistic regression model, we found associations between respiratory symptoms and traffic-related pollutants. Among those living at their current residence for at least 1 year, the adjusted odds ratio for asthma in relationship to an interquartile difference in NOX was 1.07 (95% confidence interval, 1.001.14). Thus, we found spatial variability in traffic pollutants and associated differences in respiratory symptoms in a region with good air quality. Our findings support the hypothesis that traffic-related pollution is associated with respiratory symptoms in children.

Fisk, W.J.; Seppanen, O.; Faulkner, D.; Huang, J. "Economic benefits of an economizer system: energy savings and reduced sick leave." Submitted to ASHRAE Transactions 2004. 2004. LBNL-54475 .

Abstract. Abstract: This study estimated the health, energy, and economic benefits of an economizer ventilation control system that increases outside air supply during mild weather to save energy. A model of the influence of ventilation rate on airborne transmission of respiratory illnesses was used to extend the limited data relating ventilation rate with illness and sick leave. An energy simulation model calculated ventilation rates and energy use versus time for an office building in Washington, D.C. with fixed minimum outdoor air supply rates, with and without an economiser. Sick leave rates were estimated with the disease transmission model. In the modelled 72-person office building, our analyses indicate that the economizer reduces energy costs by approximately $2000 and, in addition, reduces sick leave. The annual financial benefit of the decrease in sick leave is estimated to be between $6,000 and $16,000. This modelling suggests that economizers are much more cost effective than currently recognized.

Federspiel, C.C.; Fisk, W.J.; Price, P. N.; Liu, G.; Faulkner, D; DiBartolomeo, D.L.; Sullivan, D.P.; Lahiff, M. "Worker Performance and Ventilation in a Call Center: Analyses of Work Performance Data for Registered Nurses." Accepted for publication in Indoor Air. 2004. LBNL-55032 .

Abstract. We investigated the relationship between ventilation rates and individual work performance in a call center, and controlled for other factors of the indoor environment. We randomized

the position of the outdoor air control dampers, and measured ventilation rate, differential (indoor minus outdoor) carbon dioxide (DCO2) concentration, supply air velocity, temperature, humidity, occupant density, degree of under-staffing, shift length, time of day, and time required to complete two different work performance tasks (talking with clients and post-talk wrap-up to process information). DCO2 concentrations ranged from 13 to 611 ppm. We used multi-variable regression to model the association between the predictors and the responses. We found that agents performed talk tasks fastest when the ventilation rate was highest, but that the relationship between talk performance and ventilation was not strong or monotonic. We did not find a statistically significant association between wrap-up performance and ventilation rate. Agents were slower at the wrap-up task when the temperature was high (¿25.4 °C). Agents were slower at wrap-up during long shifts and when the call center was under-staffed.

Shendell, D.G.; Prill, R.; Fisk, W.J.; Apte, M.G.; Blake, D.; Faulkner, D. "Associations between classroom CO2 concentrations and student attendance." 2003. LBNL-53586 .

Abstract. Student attendance in American public schools is a critical factor in securing limited operational funding. Student and teacher attendance influence academic performance. Limited data exist on indoor air and environmental quality (IEQ) in schools, and how IEQ affects attendance, health, or performance. This study explored the association of student absence with measures of indoor minus outdoor carbon dioxide concentration (dCO2). Absence and dCO2 data were collected from 409 traditional and 25 portable classrooms from 14 schools located in six school districts in the states of Washington and Idaho. Study classrooms had individual heating, ventilation, and air conditioning (HVAC) systems, except two classrooms without mechanical ventilation. Classroom attributes, student attendance and school-level ethnicity, gender, and socioeconomic status (SES) were included in multivariate modeling. Forty-five percent of classrooms studied had short-term indoor CO2 concentrations above 1000 parts-per-million (ppm). A 1000 ppm increase in dCO2 was associated (p¡ 0.05) with a 0.5% to 0.9% decrease in annual average daily attendance (ADA), corresponding to a relative 10% to 20% increase in student absence. Outside air (ventilation) rates estimated from dCO2 and other collected data were not associated with absence. Annual ADA was 2% higher (p ¡ 0.0001) in traditional than in portable classrooms.

Seppänen, O.; Fisk, W.J.; Faulkner, D. "Cost benefit analysis of the night-time ventilative cooling in office building." Proceedings of the Healthy Buildings 2003 Conference, Singapore, Volume 3, Pages 394-399, Healthy Buildings 2003, Inc., Singapore. 2003. LBNL-53191 .

Abstract. The indoor temperature can be controlled with different levels of accuracy depending on the building and its HVAC system. The purpose of this study was to evaluate the potential productivity benefits of improved temperature control, and to apply the information for a cost-benefit analyses of night-time ventilative cooling, which is a very energy efficient method of reducing indoor daytime temperatures. We analyzed the literature relating work performance with temperature, and found a general decrement in work performance when temperatures exceeded those associated with thermal neutrality. These studies included physiological modelling, performance of various tasks in laboratory experiments and measured productivity at work in real buildings. The studies indicate an average 2% decrement in work performance per degree oC temperature rise, when the temperature is above 25 oC. When we use this relationship to evaluate night- time ventilative cooling, the resulting benefit to cost ratio varies from 32 to 120.

Seppänen, O.; Fisk, W.J. "A conceptual model to estimate cost effectiveness of the indoor environment improvements." Proceedings of the Healthy Buildings 2003 Conference, Singapore, Volume 3, Pages 368-374, Healthy Buildings 2003, Inc., Singapore. 2003. LBNL-53193 .

Abstract. Macroeconomic analyses indicate a high cost to society of a deteriorated indoor climate. The few example calculations performed to date indicate that measures taken to improve IEQ are highly cost-effective when health and productivity benefits are considered. We believe that cost-benefit analyses of building designs and operations should routinely incorporate health and productivity impacts. As an initial step, we developed a conceptual model that shows the links between improvements in IEQ and the financial gains from reductions in medical care and sick

leave, improved work performance, lower employee turn over, and reduced maintenance due to fewer complaints.

Mendell, M.J.; Heath, G.A. "Do indoor environments in schools influence student performance? A review of the scientific literature." Submitted to Indoor Air. 2003. LBNL-51780 .

Abstract. Limited research is available on potential adverse effects of school environments on academic performance, despite strong public concern. We examine the scientific evidence relevant to this relationship by reviewing available research relating schools and other indoor environments to human performance or attendance. As a primary focus, we critically review evidence for direct relationships between indoor environmental quality (IEQ) in buildings and performance or attendance. As a secondary focus, we summarize, without critique, evidence on potential connections indirectly linking IEQ to performance or attendance: relationships between IEQ and health, between health and performance or attendance, and between attendance and performance. The most persuasive direct evidence showed increases in indoor concentrations of nitrogen dioxide and outdoor concentrations of several specific pollutants to be related to reduced school attendance. The most persuasive indirect evidence showed indoor dampness and microbiologic pollutants to be related to asthma and respiratory infections, which have in turn been related to reduced performance and attendance. Furthermore, a substantial scientific literature links poor IEQ (e.g., low ventilation rate, excess moisture or formaldehyde) with respiratory and other health effects in children and adults. Overall, evidence suggests that poor IEQ in schools can influence the performance and attendance of students, primarily through health effects from indoor pollutants. Also, inadequate IEQ in schools seems sufficiently common to merit strong public concern. Evidence is available to justify (1) immediate actions to protect IEQ in schools and (2) focused research on exposures, prevention, and causation, to better guide policies and actions on IEQ in schools.

Mendell, MJ; Naco, GN.; Wilcox, TG.; Sieber, WK. "Environmental Risk Factors and Work-Related Lower Respiratory Symptoms in 80 Office Buildings: An Exploratory Analysis of NIOSH Data." American Journal of Industrial Medicine, Volume 43, Pages 630-641. 2003. LBNL-51761 .

Abstract. Background: We evaluated relationships between lower respiratory symptoms and risk factors for microbiological contamination in office buildings. Methods: The National Institute for Occupational Safety and Health collected data from 80 office buildings during standardized indoor environmental health hazard evaluations. Present analyses included lower respiratory symptom-based outcome definitions and risk factors for potential microbiologic contamination. Multivariate logistic regression models for selected outcomes identified key risk factors. Results: Adjusted odds ratios (95% confidence intervals) for "at least three of four work-related lower respiratory symptoms" were, for debris in ventilation air intake, 2.0 (1.0- 3.9), and for poor drainage in air-conditioning drip pans, 2.6 (1.3-5.2). Adjusted associations with risk factors were consistently stronger for outcomes requiring both multiple symptoms and improvement away from work, and somewhat stronger among diagnosed asthmatics. Conclusions: Moisture and debris in ventilation systems, possibly by supporting microbiologic growth, may increase adverse respiratory effects, particularly among asthmatics. Data from more representative buildings are needed to confirm these findings.

Fisk,W.J; Seppänen, O.; Faulkner, D.; Huang, J. "Economizer system cost effectiveness: Accounting for the influence of ventilation rate on sick leave." Proceedings of the Healthy Buildings 2003 Conference, Singapore, Volume 3, Pages 361-367, Healthy Buildings 2003, Inc., Singapore. 2003. LBNL-53192 .

Abstract. This study estimated the health, energy, and economic benefits of an economizer ventilation control system that increases outside air supply during mild weather to save energy. A model of the influence of ventilation rate on airborne transmission of respiratory illnesses was used to extend the limited data relating ventilation rate with illness and sick leave. An energy simulation model calculated ventilation rates and energy use versus time for an office building in Washington, D.C. with fixed minimum outdoor air supply rates, with and without an economiser. Sick leave rates were estimated with the disease transmission model. In the modelled 72-person office building, our analyses indicate that the economizer reduces energy costs by approximately $2000 and, in addition, reduces sick leave. The financial benefit of the decrease in sick leave is estimated to be between

$6,000 and $16,000. This modelling suggests that economizers are much more cost effective than currently recognized.

Erdmann, C.A.; Apte, M.G. "Associations of Indoor Carbon Dioxide Concentrations and Environmental Susceptibilities with Mucous Membrane and Lower Respiratory Building Related Symptoms in the BASE Study: Analyses of the 100 Building Dataset." Accepted for publication in Indoor Air Journal Special Edition 2003. 2003. LBNL-53842 .

Abstract. Using the U.S. EPA 100 office-building BASE Study dataset, we conducted multivariate logistic regression analyses to quantify the relationship between indoor CO2 concentrations (dCO2) and mucous membrane (MM) and lower respiratory system (LResp) building related symptoms, adjusting for age, sex, smoking status, presence of carpet in workspace, thermal exposure, relative humidity, and a marker for entrained automobile exhaust. In addition, we tested the hypothesis that certain environmentally-mediated health conditions (e.g., allergies and asthma) confer increased susceptibility to building related symptoms within office buildings. Adjusted odds ratios (ORs) for statistically significant, dose-dependant associations (p ¡ 0.05) for dry eyes, sore throat, nose/sinus congestion, and wheeze symptoms with 100 ppm increases in dCO2 ranged from 1.1 to 1.2. These results suggest that increases in the ventilation rates per person among typical office buildings will, on average, reduce the prevalence of several building related symptoms by up to 70%, even when these buildings meet the existing ASHRAE ventilation standards for office buildings. Building occupants with certain environmentally-mediated health conditions are more likely to experience building related symptoms than those without these conditions (statistically significant ORs ranged from 2 to 11).

Seppänen, O.; Fisk, W.J. "Relationship of SBS-symptoms and ventilation system type in office buildings." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 3, Pages 437-442, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-50046 .

Abstract. This paper provides a summary of current knowledge about the associations of ventilation system types in office buildings with sick building syndrome symptoms. Most studies completed to date indicate that relative to natural ventilation, air conditioning, with or without humidification, was consistently associated with a statistically significant increase in the prevalence of one or more SBS symptoms, by approximately 30% to 200%. In two of three analyses from a single study (assessments), symptom prevalences were also significantly higher in air-conditioned buildings than in buildings with simple mechanical ventilation and no humidification. The available data also suggest, with less consistency, an increase in risk of symptoms with simple mechanical ventilation relative to natural ventilation. The statistically significant associations of mechanical ventilation and air conditioning with SBS symptoms are much more frequent than expected from chance and also not likely to be a consequence of confounding by several potential personal, job, or building-related confounders. Multiple deficiencies in HVAC system design, construction, operation, or maintenance, including some of which cause pollutant emissions from HVAC systems, may contribute to the increases in symptom prevalences but other possible reasons remain unclear.

Mendell, M.J.; Naco, G.M.; Wilcox, T.G.; Sieber, W.K. "Building-related risk factors and work-related lower respiratory symptoms in 80 office building." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 103-108, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49566 .

Abstract. We assessed building-related risk factors for lower respiratory symptoms in office workers. The National Institute for Occupational Safety and Health in 1993 collected data during indoor environmental health investigations of workplaces. We used multivariate logistic regression analyses to assess relationships between lower respiratory symptoms in office workers and risk factors plausibly related to microbiologic contamination. Among 2,435 occupants in 80 office buildings, frequent, work-related multiple lower respiratory symptoms were strongly associated, in multivariate models, with two risk factors for microbiologic contamination: poor pan drainage under cooling coils and debris in outside air intake. Associations tended to be stronger among those with a history of physician-diagnosed asthma. These findings suggest that adverse lower respiratory health effects from indoor work environments, although unusual, may occur in relation to poorly designed or

maintained ventilation systems, particularly among previously diagnosed asthmatics. These findings require confirmation in more representative buildings.

Mendell, M.J.; Fisk, W.J.; Petersen, M.R.; Hines, C.J.; Dong, M.; Faulkner, D.; Deddens, J.A.; Ruder, A.M.; Sullivan, D.P.; Boeniger, M.F. "Indoor Particles and Symptoms Among Office Workers: Results from a Double-Blind Cross-Over Study." Epidemiology, Volume 13, Pages 296-304. 2002. LBNL-48217 .

Abstract. Background We studied the effects of removing small airborne particles in an office building without unusual contaminant sources or occupant complaints. Methods We conducted a double-blind crossover study of enhanced particle filtration in an office building in the Midwest U.S. in 1993. We replaced standard particle filters, in separate ventilation systems on two floors, with highly efficient filters, on alternate floors weekly over four weeks. Repeated-measures models were used to analyze data from weekly worker questionnaires and multiple environmental measurements. Results Bioaerosol concentrations were low. Enhanced filtration reduced concentrations of the smallest airborne particles by 94%. This reduction was not associated with reduced symptoms among the 396 respondents, but three performance-related mental states improved; for example, the confusion scale decreased (-3.7%; 95% confidence limits (CL) = -6.5, -0.9). Most environmental dissatisfaction variables also improved; eg, "stuffy" air, -5.3% (95% CL = -10.3, -0.4). Cooler temperatures within the recommended comfort range were associated with remarkably large improvement in most outcomes; for example, per 1C decrease, chest tightness decreased -23.4% (95% CL = -38.1, -8.7). Conclusions Benefits of enhanced filtration require assessment in buildings with higher particulate contaminant levels, in studies controlling for temperature effects. Benefits from lower indoor temperatures need confirmation.

Kumar, S.; Fisk, W.J. "IEQ and the impact on building occupants." ASHRAE Journal, Volume 44, Pages 50-52. 2002. LBNL-51288 .

Abstract. Research into indoor environmental quality (IEQ) and its effects on health, comfort, and performance of occupants is becoming an increasing priority as interest in high performance buildings and organizational productivity grows. Facility managers are interested in IEQ's close relationship to energy use in facilities. Employers, by providing excellent indoor environments, hope to enhance employee comfort and productivity, reduce absenteeism and health care costs, and reduce risk of litigation. The increasing interest in this field has put additional pressure on the research community as architects, engineers, facility managers, building investors, health officials, jurists, and the public seek practical guidelines on creating a safe, healthy, and comfortable indoor environment. Research on the relationships of IEQ to the health, comfort, and productivity of occupants has advanced considerably within the last decade. One of the primary goals of the Indoor Health and Productivity (IHP) Project is to communicate the results of this research, currently reported primarily in research publications, to building professionals. Consequently, the IHP project has worked with a peer review panel to select five key IHP papers and prepare summaries of these papers for publication in ASHRAE Journal. This article precedes those five summary articles, which will appear in the next five issues of the journal. This article summarizes the methodology employed to select the five papers, briefly summarizes the message of each paper, and discusses the practical implications for architects and engineers. More information about the objectives of the IHP project, results of research conducted under this project, and project sponsors and partners can be found at www.IHPCentral.org. The web site also has an online bibliography of approximately 900 papers on the topic of indoor health and productivity, drawn primarily from approximately 100 leading international journals and international conferences.

Kumar, S.; Fisk, W.J. "IEQ and the impact on employee sick leave." ASHRAE Journal, Volume 44, Pages 97-98. 2002. LBNL-51289 .

Abstract. When selecting minimum ventilation rates, employers need to strike a balance between the well-recognized energy costs of providing higher minimum ventilation rates and the expected, but less well quantified, health benefits from higher rate of ventilation. This is a summary of the paper by Milton et al. (2000) that found low employee sick leave associated with high ventilation rates in a set of buildings located in Massachusetts. A simple cost-benefit analysis is also presented.

Kumar, S.; Fisk, W.J. "The role of Emerging Energy-Efficient Technology in Promoting Workplace Productivity and Health: Final Report." 2002. LBNL-49706 .

Abstract. When selecting minimum ventilation rates, employers need to strike a balance between the well-recognized energy costs of providing higher minimum ventilation rates and the expected, but less well quantified, health benefits from higher rate of ventilation. This is a summary of the paper by Milton et al. (2000) that found low employee sick leave associated with high ventilation rates in a set of buildings located in Massachusetts. A simple cost-benefit analysis is also presented.

Heath, G.A.; Mendell, M.J. "Do Indoor Environments in Schools Influence Student Performance? A Review of the Literature." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 802-807, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49567 .

Abstract. The goal of this paper was to critically review available evidence on relationships between indoor environmental quality (IEQ) in schools and student performance. Because available evidence from schools was limited, the review expanded to include studies on direct relationships between the performance of children and adults and the indoor environments in schools, workplaces, residences, and controlled laboratory settings. The most persuasive available evidence suggests that some aspects of IEQ, including low ventilation rate and less daylight or light, may reduce the performance of occupants, including students in schools. Other evidence identifies additional possible influences, such as pollen and some carpets. Substantial limitations in the quantity and quality of available research findings suggest many questions for future study. Sufficient evidence is available to justify (1) actions to safeguard IEQ in schools and (2) the conduct of focused, well-designed research to help guide future policies and actions regarding IEQ in schools.

Fisk, W.J.; Price, P. N.; Faulkner, D; Sullivan, D; Dibartolomeo, D.; Federspiel, C.; Liu, D.L.; Lahiff, M. "Worker Performance and ventilation: analysis of time-series data for a group of call-center workers." Proceedings of the Indoor Air 2002, Monterey, CA, Volume 1, Pages 790-795, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-51724.

Abstract. We investigated the relationship of ventilation rates with the performance of advice nurses working in a call center. Ventilation rates were manipulated; temperatures, humidities, and CO2 concentrations were monitored; and worker performance data, with 30-minute resolution, were collected. Multivariate linear regression was used to investigate the association of worker performance with building ventilation rate, or with indoor CO2 concentration (which is related to ventilation rate per worker). Results suggest that the effect of ventilation rate on worker performance in this call center was very small (probably less than 1%) or nil, over most of the range of ventilation rate (roughly 12 L s-1 to 48 L s-1 per person). However, there is some evidence of worker performance improvements of 2% or more when the ventilation rate per person was very high, as indicated by the indoor CO2 concentration exceeding the outdoor concentration by less than 75 ppm.

Fisk, W.J. "How IAQ affects health, productivity." ASHRAE Journal, Volume 44, Pages 56, 58-60. 2002. LBNL-51381 .

Abstract. This article, a summary of Fisk (2000a, 2000b), estimates the nationwide improvements in health and productivity potentially attainable by providing better indoor environmental quality (IEQ) in U.S. buildings. Estimates include the potential reductions in three categories of health effects, the associated economic benefits, and the potential direct improvements in productivity not mediated through health. Expected costs and benefits of improving IEQ are compared, with a brief discussion of energy implications.

Fisk, W.J.; M.J. Mendell. "Ventilation rates and health." ASHRAE Journal, Volume 44, Pages 56-58. 2002. LBNL-51382 .

Abstract. This article summarizes the review by Seppänen et al. (1999) of current literature on the relationship of ventilation rates and carbon dioxide concentrations in non-residential and non-industrial buildings (primarily offices) with the health of the building's occupants and with the occupants' perceptions of indoor air quality (IAQ). While ventilation rates do not directly affect occupant health or perception outcomes, they affect indoor environmental conditions including air

pollutant concentrations that, in turn, may modify the occupants' health or perceptions. The review aims to provide a better scientific basis for setting health-related ventilation standards. Space constraints prohibit a detailed description of both ventilation rate and carbon dioxide concentration studies; therefore, this summary focuses primarily on the ventilation rate studies.

Federspiel, C.C.; Liu, G.; Lahiff, M.; Faulkner, D.; Dibartolomeo, D.L.; Fisk, W.J.; Price, P.N.; Sullivan, D.P. "Worker performance and ventilation: Analyses of individual data for call-center workers." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 796-801, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-50124 .

Abstract. We investigated the relationship between ventilation rates and work performance in a call center. We randomized the ventilation controls and measured ventilation rate, differential carbon dioxide (?CO2) concentration, temperature, humidity, occupant density, degree of under-staffing, shift length, time of day, and time required to complete two different work performance tasks (talk and wrap-up). ?CO2 concentrations ranged from 13 to 611 ppm. We used multi-variable regression to model the association between the predictors and the responses. We found that agents performed talk tasks fastest when the ventilation rate was highest, but that the relationship between talk performance and ventilation was not monotone. We did not find a statistically significant association between wrap-up performance and ventilation. At high temperatures agents were slower at both the talk and wrap-up tasks. Agents were slower at wrap-up during long shifts and when the call center was under-staffed.

Erdmann, C.A.; Steiner, K.C.; Apte, M.G. "Indoor carbon dioxide concentrations and SBS symptoms in office buildings revisited: Analyses of the 100 building BASE Study dataset." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 3, Pages 443-448, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49584 .

Abstract. In previously published analyses of the 41-building 1994-1996 USEPA Building Assessment Survey and Evaluation (BASE) dataset, higher workday time-averaged indoor minus outdoor CO2 concentrations (dCO2) were associated with increased prevalence of certain mucous membrane and lower respiratory sick building syndrome (SBS) symptoms, even at peak dCO2 concentrations below 1,000 ppm. For this paper, similar analyses were performed using the larger 100-building 1994-1998 BASE dataset. Multivariate logistic regression analyses quantified the associations between dCO2 and the SBS symptoms, adjusting for age, sex, smoking status, presence of carpet in workspace, thermal exposure, relative humidity, and a marker for entrained automobile exhaust. Adjusted dCO2 prevalence odds ratios for sore throat and wheeze were 1.17 and 1.20 per 100-ppm increase in dCO2 (p ¡0.05), respectively. These new analyses generally support our prior findings. Regional differences in climate, building design, and operation may account for some of the differences observed in analyses of the two datasets.

Seppänen, O.; Fisk, W.J. "Association of ventilation system type with SBS symptoms in office workers." Indoor Air, Volume 12, Pages 98-112. 2001. LBNL-47457 .

Apte, M G.; Lefohn, A.S. "Letters to the Editor." Journal of the Air and Waste Management Association, Volume 50, Pages 322. 2001.

Wyon, D.; Fisk, W.J.; Rautio, S. "Research needs and approaches pertaining to the indoor climate and productivity." Healthy Buildings 2000, Volume 2, Pages 327-332, SIY Indoor Air Information. 2000. LBNL-48219.

Abstract. The indoor environment affects the health, comfort and performance of occupants. All three are important, but the cost of improved design, operation, maintenance and energy use in buildings must usually be justified in terms of the expected effects on productivity. While there is no doubt that effects on health, comfort and performance translate into effects on productivity, there is an urgent need to discover which of the hypothesised mechanisms of cause and effect are valid to quantify how much each mechanism affects productivity in different work situations, and to validate predictions in the field.

Seppanen, O.; Fisk, B. "Association of ventilation rates with health and other responses in commercial and institutional buildings." Healthy Buildings 2000 Conference, Volume Workshop Summaries, Pages 1-8, SIY Indoor Air Information, Oy Helsinki, Finland. 2000. LBNL-48246.

Fisk, W.J. "Review of health and productivity gains from better IEQ." Healthy Buildings 2000, Volume 4, Pages 23-24, SIY Indoor Air Information. 2000. LBNL-48218.

Abstract. The available scientific data suggest that existing technologies and procedures can improve indoor environmental quality (IEQ) in a manner that significantly increases productivity and health. While there is considerable uncertainty in the estimates of the magnitudes of productivity gains that may be obtained, the projected gains are very large. For the U.S., the estimated potential annual savings and productivity gains are $6 to $14 billion from reduced respiratory disease, $2 to $4 billion from reduced allergies and asthma, $10 to $30 billion from reduced sick building syndrome symptoms, and $20 to $160 billion from direct improvements in worker performance that are unrelated to health. Productivity gains that are quantified and demonstrated could serve as a strong stimulus for energy efficiency measures that simultaneously improve the indoor environment.

Fisk, W.J. "Health and productivity gains from better indoor environments and their relationship with building energy efficiency." Annual Review of Energy and the Environment, Volume 25, Pages 537-566. 2000. LBNL-45484.

Fisk, W.J. "Estimates of potential nationwide productivity and health benefits from better indoor environments: An update." Chapter 4 in Indoor Air Quality Handbook, McGraw Hill, New York. 2000. LBNL-42123.

Apte, M.; Fisk, W.; Daisey, J. "Indoor carbon dioxide concentrations and SBS in office workers." Proceedings of the Healthy Buildings 2000 Conference, Helsinki, Finland, Volume 1, Pages 133-138, SIY Indoor Air Information, Oy, Helsinki, Finland. 2000. LBNL-45019 .

Apte, M.; Fisk, B.; Daisey, J. "Associations between Indoor CO2 Concentrations and Sick Building Syndrome Symptoms in US Office Buildings: An Analysis of the 1994-1996 BASE Study Data." Indoor Air, Volume 10, Pages 246-257. 2000. LBNL-44385 .

Seppänen, O.A.; Fisk, W.J.; Mendell, M.J. "Association of ventilation rates and CO2 -concentrations with health and other responses in commercial and institutional buildings." Indoor Air, Volume 9, Pages 226-252. 1999. LBNL-43334 .

Mendell, M. J.; Fisk, W. J.; Petersen, M.; Hines, C. J.; Faulkner, D.; Deddens, J. A.; Dong, M. X.; Ruder, A. M.; Sullivan, D.; Boeniger, M. F. "Effects on Occupants of Enhanced Particle Filtration in a Non-Problem Office Environment: A Double-Blind Crossover Intervention Study." The American Journal of Industrial Medicine, Volume Supp 1, Pages 55-57. 1999. LBNL-42221.

Apte, M.G. "VOCs and "Sick Building Syndrome": Application of a New Statistical Approach for SBS Research to U.S. EPA BASE Study Data." Proceedings of the Indoor Air '99, Edinburgh, Scotland, Volume 1, Pages 117-112, Construction Research Communications, Ltd., London. 1999. LBNL-42698 .

Fisk, W.J.; A.H. Rosenfeld. "Potential Nationwide Improvements in Productivity and Health from Better Indoor Environments." Proceedings of the 1998 ACEEE Summer Study on Energy and Efficiency in Buildings, Pacific Grove, CA, Volume 8, Pages 85-97, American Council for an Energy Efficient Economy, Washington, DC. 1998. LBNL-41849.

Fisk, W.J.; Rosenfeld, A.H. "The indoor environment – productivity and health – and $$$." Planning for Energy and the Environment, Volume 17, Pages 53-57. 1998.

Fisk, W.J.; D. Faulkner; D. Sullivan; M. Dong; C. Dabrowski, Jr.; J.J. Thomas; M.J. Mendell; C.J. Hines; A. Ruder; M. Boeniger. "The healthy building intervention study: Objectives, methods and results of Selected Environment Measurements." 1998. LBNL-41546.

Fisk, W.J.; Rosenfeld, A.H. "Estimates of Improved Productivity and Health from Better Indoor Environments." Indoor Air, Volume 7, Pages 158-172. 1997. LBNL-39596.

Mendell, MJ; Fisk, WJ; Deddens, JA; Seavey, WG; Smith AH; Smith DF; Hodgson, AT; Daisey JM; Goldman L. "Elevated symptom prevalence associated with ventilation type in office buildings: findings from the California Healthy Building Study." Epidemiology, Volume 7, Pages 583-589. 1996. LBNL-42555.

Ten Brinke, J. "Development of New VOC Exposure Metrics and their Relationship to "Sick Building Syndrome" Symptoms." Environmental Health Sciences, School of Public Health, Pages 223, University of California, Berkeley. 1995. LBNL-37652.

2.3. Indoor Environmental Quality

Apte, M G.; Hodgson, A.T; Shendel, D.G.; Rainer, L.I.; Hoeschele, M.A. "Designing Building Systems to Save Energy and Improve Indoor Environments: A Practical Demonstration." Submitted to 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy, Washington, DC. 2004. LBNL-54859 .

Abstract. Building design concepts that focus on energy efficiency may conflict with those intended to provide excellent indoor environmental quality (IEQ). Careful selection of a heating, ventilating, and air-conditioning (HVAC) system, and low-emission interior finish materials, can result in winwin designs that minimize tradeoffs between energy and IEQ. We demonstrated energy and IEQ benefits in four new relocatable classrooms (RCs) monitored in two climate regions of California for one year. We used a case-crossover experimental design to compare energy and IEQ characteristics of a hybrid HVAC system that provides continuous ventilation (indirect-direct evaporative cooler with high-efficiency hydronic gas heat) to a standard heat pump system. Additionally, we explored the IEQ benefits of measurement-based selection of interior finish materials with low emissions of health-relevant volatile organic compounds (VOCs) including formaldehyde. Monitored data were used to calibrate DOE-2 models that simulated California-wide energy saving potential of RCs employing energy efficient building components including the hybrid HVAC system. IEQ monitoring results from our field investigation indicated that VOC concentration reductions, typically 50% or more, were achieved through improved ventilation while simultaneously average cooling and heating energy costs were reduced by 50% and 30%, respectively. Incremental annual California-wide energy impacts from installation of hybrid HVAC systems in 4,000 new RCs were projected to be: 5,975 MWh of electricity savings; 23.8 MW winter and 13.1 MW summer peak electric load reduction; 1,025 MBtu natural gas consumption from switch to gas heating; 50,931 MBtu source energy reduction; and a combined school district annual operating cost reduction of $880,900.

Shendell, D.G. "Assessment of organic compound exposures, thermal comfort parameters, and HVAC system-driven air exchange rates in public school portable classrooms in California." 2003. LBNL-53804 .

Abstract. The prevalence of prefabricated, portable classrooms (portables, relocatables, RCs) has increased due to class size reduction initiatives and limited resources. Classroom mechanical wall-mount heating, ventilation, and air conditioning (HVAC) systems may function improperly or not be maintained; lower ventilation rates may impact indoor air and environmental quality (IEQ). Materials in portables may off- gas volatile organic compounds (VOCs), including formaldehyde, as a function of age, temperature, and humidity. For a pilot study, public K-12 schools located in or serving target areas within five Los Angeles County communities were identified. In two communities where school districts (SD) consented, 1-3 randomly selected portables, one newer and one older, and one main building control classroom from each participating school were included. Sampling was conducted over a five-day school week in the cooling and heating seasons, or repeated twice in the cooling season. Measurements included passive samplers for VOCs, formaldehyde and acetaldehyde, and air exchange rate (AER) calculation; indoor air temperature and humidity; technician walk-through surveys; an interview questionnaire about HVAC system operation and maintenance (O&M). For an intervention study evaluating advanced HVAC technologies in comparison to the common conventional technology, and materials for source reduction of VOCs, four RC were manufactured and located in pairs at two schools in two recruited Northern California SD in different climate zones. RCs were built with the two HVAC systems, cabinetry and conduit for monitoring equipment, and standard or advanced interior finish materials. Each RC was its own control in

a case-crossover design – HVAC systems alternately operated for 1-2 week intervals in the 2001-02 school year, with IEQ monitoring including aldehyde and indoor air temperature and humidity data. Measured classroom AER were low, formaldehyde concentrations were below the state indoor air guideline "target level," and concentrations of most target VOCs were low. O&M questionnaire results suggested insufficient training and communication between custodians and SD offices concerning HVAC systems. Future studies should attempt larger sample sizes and cover larger geographical areas but continue to assess multiple IEQ parameters during occupied hours. Teachers, custodians, and SD staff must be educated on the importance of adequate ventilation with filtered outdoor air.

Daisey, J.; Apte, M G.; Angell, W.J. "Indoor air quality, ventilation and health symptoms in schools: An analysis of existing information." Indoor Air, Volume 13, Pages 53-64. 2003. LBNL-48287 .

Abstract. We reviewed the literature on indoor air quality (IAQ), ventilation, and building-related health problems in schools and identified commonly reported building-related health symptoms involving schools until 1999. We collected existing data on ventilation rates, carbon dioxide (CO2) concentrations and symptom-relevant indoor air contaminants, and evaluated information on causal relationships between pollutant exposures and health symptoms. Reported ventilation and CO2 data strongly indicate that ventilation is inadequate in many classrooms, possibly leading to health symptoms. Adequate ventilation should be a major focus of design or remediation efforts. Total volatile organic compounds, formaldehyde and microbiological contaminants are reported. Low formaldehyde concentrations were unlikely to cause acute irritant symptoms (¡0.05 ppm), but possibly increased risks for allergen sensitivities, chronic irritation, and cancer. Reported microbiological contaminants included allergens in deposited dust, fungi and bacteria. Levels of specific allergens were sufficient to cause symptoms in allergic occupants. Measurements of airborne bacteria and airborne and surface fungal spores were reported in schoolrooms. Asthma and "sick building syndrome" symptoms are commonly reported. The few studies investigating causal relationships between health symptoms and exposures to specific pollutants suggest that such symptoms in schools are related to exposures to volatile organic compounds (VOCs), molds and microbial VOCs, and allergens.

Apte, M G.; Hodgson, A.; Shendel, D.G.; Dibartolomeo, D.; Hotchi, T.; Lee, S-M; Liff, S.; Rainer, L.; Sullivan, D; Fisk, W.J. "Simultaneous Improvements in Relocatable Classrooms." ASHRAE IAQ Applications, Pages 7-10. 2003. LBNL-54870 .

Apte, M.G.; Hodgson, A.T.; Shendell, D.G.; Dibartolomeo, D.; Hotchi, T.; Lee, S.M.; Liff, S.M.; Rainer, L.I.; Sullivan, D.P.; Fisk, W.J.. "Simultaneous Energy Savings and IEQ Improvements in Relocatable Classrooms." 2003. LBNL-52690 .

Abstract. Relocatable classrooms (RCs) are commonly used by school districts with changing demographics and enrollment sizes. We designed and constructed four energy-efficient RCs for this study to demonstrate technologies with the potential to simultaneously improve energy efficiency and indoor environmental quality (IEQ). Two were installed at each of two school districts, and energy use and IEQ parameters were monitored during occupancy. Two RCs (one per school) were finished with materials selected for reduced emissions of toxic and odorous volatile organic compounds (VOCs). Each had two HVAC systems, operated on alternate weeks, consisting of a standard heat-pump system and an indirect-direct evaporative cooling (IDEC) system with gas-fired hydronic heating. The IDEC system provides continuous outside air ventilation at "15 CFM (7.5 L s-1) person-1, efficient particle filtration while using significantly less energy for cooling. School year long measurements included: carbon dioxide (CO2), particles, VOCs, temperature, humidity, thermal comfort, noise, meteorology, and energy use. IEQ monitoring results indicate that important ventilation-relevant indoor CO2 and health-relevant VOC concentration reductions were achieved while average cooling and heating energy costs were simultaneously reduced by 50% and 30%, respectively.

IED Staff. "A compilation of papers for the Indoor Air 2002 Conference in memory of Joan M. Daisey." 2002. LBNL-50419 .

Abstract. No Abstract available

Shendell, DG; Lee, S-M; Apte, MG; DiBartolomeo, DB; Sullivan, DP; Liff, SM; Fisk, WJ; Rainer, LI. "Assessment of Noise Exposures in New Relocatable Classrooms with Standard and Advanced HVAC Systems." Epidemiology, Volume 13, Pages S223. 2002. Abstract (no LBNL number).

Abstract. Anecdotal evidence suggests heating, ventilation, and air conditioning (HVAC) systems in modular classrooms are not operated effectively. Teachers are usually in charge of thermal control. Due to inadequate training in HVAC system operation and indoor environmental quality (IEQ) issues, and the relatively loud noise produced by the HVAC system while meeting cooling or heating demands, teachers may avoid using mechanical ventilation. Adequate ventilation is an important link between improved IEQ and energy efficiency for schools. Indoor air quality and physical environmental stresses including noise can adversely impact the health of young children and teachers. During the school year these occupants spend the majority of the 7-8 hour school day inside their classrooms. Therefore, classroom noise levels can be assumed to drive personal school day exposures. As part of a field project of IEQ and energy efficiency, we investigated noise levels in four new relocatable classrooms (RCs). The RCs were equipped with both standard and advanced HVAC systems, alternately operated in a case-crossover study design. Classroom noise data, measured as A-weighted decibels (dB(A)), were collected continuously for the 2001-02 school year with sound level meters (SLM; Extech #407736, Type II, 1.5 dB(A) accuracy, 0.1 dB(A) resolution). A SLM was suspended downward below the ceiling at the center of each 960 ft2 RC from a specially designed mobile located 7.0 ft above the floor. The microphone placement and orientation complied with ANSI and IEC specifications; weekly calibration was performed. Reflectance off ceiling tiles, walls, and student desks were negligible. Descriptive statistics were calculated for each classroom for six distinct time periods: start of school day to recess; recess to lunch; the unoccupied lunch period; lunch to end of school day; overnight; and, weekend. Data were stratified by HVAC system in operation and summarized for four periods: fall cooling season; fall-to-winter transitional period; winter heating season; and spring. This study suggests HVAC systems and occupants were the dominant sources of noise exposure for the RCs indoor environment. In the cooling season, at one school, school-day time-weighted average (Leq) values, in dB(A), were 60.0 and 61.0; at the other school, the values in September were 52.2 and 55.7, and in October were 54.3 and 56.0. Examining specific early morning and lunch periods when HVAC systems were on but RCs unoccupied, the advanced system contributed less noise (4-8 dB(A)) than the standard system (10-15 dB(A)). Mean observed classroom noise levels for several time periods, as well as school-day and school morning Leq values, exceeded existing school district, state, and international guidelines of 40-50 dB(A).

Shendell, D.G.; DiBartolomeo, D.; Fisk, W.J.; Hodgson, A.T.; Hotchi, T.; Lee, S. M.; Sullivan, D.P.; Apte, M.G.; Rainer, L.I. "Final methodology for a field study of indoor environmental quality and energy efficiency in new relocatable classrooms in Northern California." 2002. LBNL-51101 .

Abstract. The prevalence of relocatable classrooms (RCs) at schools is rising due to federal and state initiatives to reduce K-3 class size, and limited capital resources. Concerns regarding inadequate ventilation and indoor air and environmental quality (IEQ) in RCs have been raised. Adequate ventilation is an important link between improved IEQ and energy efficiency for schools. Since students and teachers spend the majority of a 7-8 hour school day inside classrooms, indoor contaminant concentrations are assumed to drive personal school-day exposures. We conducted a demonstration project in new relocatable classrooms (RCs) during the 2001-02 school year to address these issues. Four new 24' x 40' (960 ft2) RCs were constructed and sited in pairs at an elementary school campus in each of two participant school districts (SD) in Northern California. Each RC was equipped with two heating, ventilation, and air conditioning (HVAC) systems, one per module. The two HVAC systems were a standard heat pump with intermittent 25-50% outdoor air ventilation and an energy-efficient advanced system, based on indirect-direct evaporative cooling with an integrated natural gas-fired hydronic heating loop and improved particle filtration, providing continuous 100% outdoor air ventilation at = 15 ft3 min-1 occupant-1. Alternate carpets, wall panels, and ceiling panels were installed in two classrooms - one in each pair - based on the results of a laboratory study of VOC emissions from standard and alternate materials. Numerous IEQ and outdoor air quality and meteorological parameters were measured either continuously over the school year or as integrated school day samples during the fall cooling and winter heating seasons. Details of the RC

designs, the field monitoring methodology including handling, storage, transport and management of chemical samples and data, and analyses to be conducted are presented.

Shendell, D.G.; Apte, M.G.; Kim, J.; Smorodinsky, S. "Building effective partnerships to conduct school indoor environmental quality assessments and interventions." 2002. LBNL-50377 .

Abstract. Public, private, government, and university stakeholders have focused increasing attention on children's environmental health. Priority areas include healthy school environments; susceptibilities of children to environmental factors and associated illness; and, understanding exposure to biological, chemical, and physical agents. As multidisciplinary teams, we have conducted studies and intervention demonstrations in California public schools. A common theme among them was a "partnership," the collaboration between stakeholders from the aforementioned sectors. Federal funding and local bond measures for planning, maintenance, and modernization of school facilities have recently been authorized. Therefore, beneficial "partnerships" should be established to conduct needed IEQ, environmental health, and productivity research, development and demonstration. This field action report describes benefits for stakeholders and five strategies for future effective collaborations.

Fisk, W.J.; Faulkner, D; Sullivan, D; Delp, W. "Measuring rates of outdoor airflow into HVAC systems." 2002. LBNL-51583 .

Abstract. During the last few years, new technologies have been introduced for measuring the flow rates of outside air into HVAC systems. This document describes one particular technology for measuring these airflows, a system and a related protocol developed to evaluate this and similar measurement technologies under conditions without wind, and the results of our evaluations. We conclude that the measurement technology evaluated can provide a reasonably accurate measurement of OA flow rate over a broad range of flow, without significantly increasing airflow resistance.

Fisk, W.J.; Brager, G.; Brook, M.; Burge, H.; Cole, J.; Cummings, J.; Levin, H.; Loftness, V.; Logee, T.; Mendell, M.J.; Persily, A.; Taylor, S.; Zhang, J. "A priority agenda for energy-related indoor environmental quality research." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 2, Pages 984-989, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-50612 .

Abstract. A multidisciplinary team of IEQ and energy researchers is working together to define a program of priority energy-related IEQ research. This paper describes the methods employed, ten high priority broad research and development (R&D) goals, and 34 high priority R&D project areas linked to these goals.

Apte, M.; Hodgson, A.; Shendell, D.; Dibartolomeo, D.; Hotchi, T.; Kumar, S.; Lee, S.M.; Liff, S.; Rainer, L.; Schmidt, R.; Sullivan, D.; Diamond, R.; Fisk, W.J. "Energy and indoor environmental quality in relocatable classrooms." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 2, Pages 62-69, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49581 .

Abstract. Relocatable classrooms (RCs) are commonly utilized by school districts with changing demographics and enrollment sizes. Four energy-efficient RCs were designed and constructed for this study to demonstrate technologies that simultaneously attempt to improve energy efficiency and indoor environmental quality (IEQ). Two were installed at each of two school districts, and energy use and IEQ parameters were monitored during occupancy. Two (one per school) were finished with materials selected for reduced emissions of toxic and odorous volatile organic compounds (VOCs). Each RC had two HVAC systems, alternated weekly, consisting of a standard heat-pump system and an indirect-direct evaporative cooling (IDEC) system with gas-fired hydronic heating. The hypothesized advantages of the IDEC include continuous outside air ventilation at ?7.5 L s-1 per person, 70% less cooling energy and efficient particle filtration. Measurements include: carbon dioxide, particles, VOCs, temperature, humidity, thermal comfort, noise, meteorology, and energy use. Preliminary IEQ monitoring results are reported.

Shendell, D.G.; M.G. Apte; D. DiBartolomeo; W. J. Fisk; A.T. Hodgson; S. Kumar; D.P. Sullivan; L.I. Rainer. "Linking Energy Efficiency and Indoor Environmental Quality to Provide Thermal Comfort and Reduce Children's Exposure to Volatile Organic Compounds: Demonstration Project in New Relocatable

Classrooms at Northern California Public Schools." Proceedings of the 11th Annual Meeting of the International Society for Exposure Analysis, Charleston, SC, Pages 148, International Society for Exposure Analysis, Boston, MA. 2001.

Shendell, D.G.; Apte, M.G.; Corsi, R.; Jenkins, M.P.; Kim, J.; Smorodinsky, S.; Torres, V.; J.M. Waldman. "Studying the Public School Environment and Classroom Indoor Air Quality: Community-based Exposure Assessments Through Public-Private-Government Partnerships, Examples from CA and TX." 2001.

Apte, M.G.; Fisk, W.J.; Hodgson, A.T.; Russell, M.; Shendell. D.G. "California Demonstration Energy Efficiency-Indoor Environmental Quality Project: Predicted Relocatable Classroom Indoor Air Quality due to Low-Emitting Interior Materials and Enhanced Ventilation." Proceedings of the 11th Annual Meeting of the International Society of Exposure Analysis, Charleston, SC, International Society for Exposure Analysis, Boston, MA. 2001.

IED Staff. "Recent Research on Indoor Air Quality: A Compilation in Memory of Joan Daisey." 2000. LBNL-45463.

Fisk, W.J.; Faulkner D.; Sullivan, D.; Mendell, M.J. "Particle concentrations and sizes with normal and high efficiency filtration in a sealed air-conditioned office building." Aerosol Science & Technology, Volume 32, Pages 527-544. 2000. LBNL-43835.

Hines, C.J.; Milton, D.K.; Larsson, L.; Petersen, M.R.; Fisk, W.J.; Mendell, M.J. "Characterization of endotoxin and 3-hydroxy fatty acids in an office building." Indoor Air, Volume 10, Pages 2-12. 1999.

Daisey, J. "Indoor Air Quality, Ventilation and Health Symptoms in Schools: An Analysis of Existing Information." Proceedings of the Indoor Air '99, Edinburgh, Scotland, Volume 2, Pages 1-6, Construction Research Communications, Ltd., London. 1999.

Apte, M.G.; Hammond, S.K.; Gundel, L.A.; Cox, D. "A New Carbon Monoxide Occupational Dosimeter: Results from a Worker Exposure Assessment Survey." Journal of Exposure Analysis and Environmental Epidemiology, Volume 9, Pages 546-559. 1999. LBNL-43832.

Faulkner, D.; W.J. Fisk; A.J. Gadgil; D.P. Sullivan. "Demonstration and Field Test of air jacket technology." 1998. LBNL-42099.

Daisey, J.M.; Angell, W.J. "Survey and Critical Review of the Literature on Indoor Air Quality, Ventilation and Health Symptoms in Schools." 1998. LBNL-41517.

2.4. Thermal Distribution Systems (Ducts)

Walker, I.S.; Sherman, M.; Dickerhoff, D. "Reducing Uncertainty for the DeltaQ Duct Leakage Test." Submitted to Performance of Exterior Envelopes of Whole Buildings IX International Conference, Clearwater Beach, FL, ASHRAE, Atlanta, GA. 2004. LBNL-53549 .

Abstract. The thermal distribution system couples the HVAC components to the building envelope, and shares many properties of the buildings envelope including moisture, conduction and most especially air leakage performance. Duct leakage has a strong influence on air flow rates through building envelopes (usually resulting in much greater flows than those due to natural infiltration) because unbalanced duct air flows and leaks result in building pressurization and depressurization. As a tool to estimate this effect, the DeltaQ duct leakage test has been developed over the past several years as an improvement to existing duct pressurization tests. It focuses on measuring the air leakage flows to outside at operating conditions that are required for envelope infiltration impacts and energy loss calculations for duct systems. The DeltaQ test builds on the standard envelope tightness blower door measurement techniques by repeating the tests with the system air handler off and on. The DeltaQ test requires several assumptions to be made about duct leakage and its interaction with the duct system and building envelope in order to convert the blower door results into duct leakage at system operating conditions. This study examined improvements to the DeltaQ test that account for some of these assumptions using a duct system and building envelope in a test laboratory. The laboratory measurements used a purpose-built test chamber coupled to a

duct system typical of forced air systems in US homes. Special duct leaks with controlled air-flow were designed and installed into an airtight duct system. This test apparatus allowed the systematic variation of the duct and envelope leakage and accurate measurement of the duct leakage flows for comparison to DeltaQ test results. This paper will discuss the laboratory test apparatus design, construction and operation, the various analysis techniques applied to the calculation procedure and present estimates of uncertainty in measured duct leakage.

Diamond, R.C.; Wray, C.P.; Smith, B.V.; Dickerhoff, D.J.; Matson, N.E.; Cox, S.A. "A prototype data archive for the pier "thermal distribution systems in commercial buildings" project." 2004. LBNL-54191 .

Abstract. A prototype archive for a selection of building energy data on thermal distribution systems in commercial buildings was developed and pilot tested. While the pilot demonstrated the successful development of the data archive prototype, several questions remain about the usefulness of such an archive. Specifically, questions on the audience, frequency of use, maintenance, and updating of the archive would need to be addressed before this prototype is taken to the next level.

Wray, Craig P.; Matson, Nance E. "Duct Leakage Impacts on VAV System Performance in Large Commercial Buildings." 2003. LBNL-53605 .

Abstract. The purpose of this study is to evaluate the variability of duct leakage impacts on air distribution system performance for typical large commercial buildings in California. Specifically, a hybrid DOE-2/TRNSYS sequential simulation approach was used to model the energy use of a low-pressure terminal-reheat variable-air-volume (VAV) HVAC system with six duct leakage configurations (tight to leaky) in nine prototypical large office buildings (representing three construction eras in three California climates where these types of buildings are common). Combined fan power for the variable-speed-controlled supply and return fans at design conditions was assumed to be 0.8 W/cfm. The VAV system that we simulated had perfectly insulated ducts, and maintained constant static pressure in the ducts upstream of the VAV boxes and a constant supply air temperature at the air-handler. Further evaluations of duct leakage impacts should be carried out in the future after methodologies are developed to deal with duct surface heat transfer effects, to deal with airflows entering VAV boxes from ceiling return plenums (e.g., to model parallel fan-powered VAV boxes), and to deal with static pressure reset and supply air temperature reset strategies.

Wray, Craig P. "Duct Thermal Performance Models for Large Commercial Buildings." 2003. LBNL-53410 .

Abstract. Despite the potential for significant energy savings by reducing duct leakage or other thermal losses from duct systems in large commercial buildings, California Title 24 has no provisions to credit energy-efficient duct systems in these buildings. A substantial reason is the lack of readily available simulation tools to demonstrate the energy- saving benefits associated with efficient duct systems in large commercial buildings.

Diamond, R.C.; Wray, C.P.; Dickerhoff, D.J.; Matson, N.E.; Wang, D. "Thermal distribution systems in commercial buildings." 2003. LBNL-51860 .

Abstract. Previous research suggests that HVAC thermal distribution systems in commercial buildings suffer from thermal losses, such as those caused by duct air leakage and poor duct location. Due to a lack of metrics and data showing the potentially large energy savings from reducing these losses, the California building industry has mostly overlooked energy efficiency improvements in this area. The purpose of this project is to obtain the technical knowledge needed to properly measure and understand the energy efficiency of these systems. This project has three specific objectives: to develop metrics and diagnostics for determining system efficiencies, to develop design and retrofit information that the building industry can use to improve these systems, and to determine the energy impacts associated with duct leakage airflows in an existing large commercial building. The primary outcome of this project is the confirmation that duct leakage airflows can significantly impact energy use in large commercial buildings: our measurements indicate that adding 15% duct leakage at operating conditions leads to an increase in fan power of about 25 to 35%. This finding is consistent with impacts of increased duct leakage airflows on fan power that have been predicted

by previous simulations. Other project outcomes include the definition of a new metric for distribution system efficiency, the demonstration of a reliable test for determining duct leakage airflows, and the development of new techniques for duct sealing. We expect that the project outcomes will lead to new requirements for commercial thermal distribution system efficiency in future revisions of California's Title 24.

Xu, T.T.; Carrie, F.R.; Dickerhoff, D.J.; Fisk, W.J.; McWilliams, J.; Wang, D.; Modera, M.P. "Performance of thermal distribution systems in large commercial buildings." Energy and Buildings, Volume 34, Pages 215-226. 2002. LBNL-44331 .

Abstract. This paper presents major findings of a field study on the performance of five thermal distribution systems in four large commercial buildings. The five systems studied are typical single-duct or dual-duct constant air volume (CAV) systems and variable air volume (VAV) systems, each of which serves an office building or a retail building with floor area over 2,000 m2. The air leakage from ducts are reported in terms of effective leakage area (ELA) at 25 Pa reference pressure, the ASHRAE-defined duct leakage class, and air leakage ratios. The specific ELAs ranged from 0.7 to 12.9 cm2 per m2 of duct surface area, and from 0.1 to 7.7 cm2 per square meter of floor area served. The leakage classes ranged from 34 to 757 for the five systems and systems sections tested. The air leakage ratios are estimated to be up to one-third of the fan- supplied airflow in the constant-air-volume systems. The specific ELAs and leakage classes indicate that air leakage in large commercial duct systems varies significantly from system to system, and from system section to system section even within the same thermal distribution system. The duct systems measured are much leakier than the ductwork specified as "unsealed ducts" by ASHRAE. Energy losses from supply ducts by conduction (including convection and radiation) are found to be significant, on the scale similar to the losses induced by air leakage in the duct systems. The energy losses induced by leakage and conduction suggest that there are significant energy-savings potentials from duct-sealing and insulation practice in large commercial buildings.

Sherman, M.H.; Xu, T.T.; Abushakra, B.; Dickerhoff, D.J.; Wang, D.M.; Wray, C.P.; Modera, M.P. "Thermal Distribution System Characteristics and Energy Impacts of Duct Leaks in Light Commercial Buildings." 2002. LBNL-49470.

Abstract. No Abstract Available

Carrie, F. R.; Levinson, R.; Xu, T. T.; Dickerhoff, D. J.; Fisk, W. J.; McWilliams, J.; Modera, M. P.; Wang, D. "Laboratory and field testing of an aerosol-based duct-sealing technology for large commercial buildings." ASHRAE Transactions. 2002. LBNL-44220 .

Abstract. Laboratory and field experiments were performed to evaluate the feasibility of sealing leaks in commercial duct systems with an aerosol sealant. The method involves blowing an aerosol through the duct system to seal the leaks from the inside, the principle being that the aerosol particles deposit in the cracks as they try to escape under pressure. It was shown that the seals created with the current sealant material can withstand pressures far in excess of what is found in commercial-building duct systems. We also performed two field experiments in two large-commercial buildings. The ASHRAE leakage classes of the systems were reduced from 653 down to 103, and from 40 down to 3. Methods and devices specifically devised for this application proved to be very efficient at (a) increasing the sealing rate and (b) attaining state-of-the-art duct leakage classes. Additional research is needed to improve the aerosol injection and delivery processes.

Modera, M.P; Brzozowski, O; Carrie, F.R; Dickerhoff, D.J; Delp, W.W; Fisk, W.J; Levinson, R; Wang, D. "Sealing Ducts in Large Commercial Buildings with Aerosolized Sealant Particles." Energy & Buildings, Volume 34, Pages 705-714. 2001. LBNL-42414 .

Carrie, F.R.; Modera, M.P. "Experimental investigation of aerosol deposition on slot-and joint-type leaks." Journal of Aerosol Science, Volume 33, Pages 1447-1462. 2001. LBNL-48774 .

Xu, T. "Commercial Thermal Distribution Systems: Final Report for CIEE/CEC." 2000. LBNL-45080 .

Xu, T. "Performance Diagnostics of Thermal Distribution Systems in Light Commercial Buildings: Final Report for CIEE/CEC." Proceedings of the ACEEE 2000 Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 3, Pages 383-394, American Council for an Energy Efficient Economy, Washington, DC. 2000. LBNL-45080 .

Levinson, R.M.; Delp, W.W.; Dickerhoff, D.J.; Modera, M.P. "Effects of air infiltration on the effective thermal conductivity of internal fiberglass insulation and on the delivery of thermal capacity via ducts." 2000. LBNL-42499 .

Levinson, R.; Delp, W.; Dickerhoff, D.; Modera, M. "Effects of Airflow Infiltration on the Thermal Performance of Internally-insulated Ducts." Energy & Buildings, Volume 32, Pages 345-354. 2000. LBNL-45447.

Fisk, W.J.; Delp, W.W.; Diamond, R.C.; Dickerhoff, D.J.; Levinson, R.; Modera, M.P.; Nematollahi, M.; Wang, D. "Duct systems in large commercial buildings: physical characterization, air leakage and heat conduction gains." Energy & Buildings, Volume 32, Pages 109-119. 2000. LBNL-42339 .

Xu, T. "Duct System Performance and Energy Losses in Large Commercial Building." 1999. LBNL-44221 .

Modera, M.; Xu, T.; Feustel, H.E.; Matson, N.E.; Huizenga, C.; Baumann, F.; Arens, E. "Efficient thermal energy distribution in commercial buildings – Final Report." 1999. LBNL-41365 .

Franconi, Ellen. "Measuring advances in HVAC distribution system designs." 1998. LBNL-43188.

Franconi, E. "Measuring Advances in HVAC Distribution System Design." Proceedings of the 1998 ACEEE Summer Study on Energy and Efficiency in Buildings, Pacific Grove, CA, Volume 3, Pages 153-165, American Council for an Energy Efficient Economy, Washington, DC. 1998. LBNL-41956.

Delp, W.W.; Matson, N.E.; Modera, M.P. "Exterior Exposed Ductwork: Delivery Effectiveness and Efficiency." ASHRAE Transactions, Volume 104, Pages 709-721. 1998. LBNL-39083 .

Levinson, R.; Delp, W.; Dickerhoff, D.; Fisk, W.; Nematollahi, M.; Stordahl, I.; Torre, C.; Wang, D.; Diamond, R.; Modera, M. "Commercial Thermal Distribution Systems: Final Report for CIEE." 1997. LBNL-40105.

Delp, W.; Matson, N.; Tschudy, E.; Modera, M.; Diamond, R. "Field Investigation of Duct System Performance in California-Light Commercial Buildings." 1997. LBNL-40102 .

Walker, I.; Modera, M.; Tuluca, A.; Graham, I. "Energy effectiveness of duct sealing and insulation in two multifamily buildings." Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 1, Pages 247-254, American Council for an Energy Efficient Economy, Washington, DC. 1996. LBL-38538 .

Abstract. Energy losses from forced air distribution systems have a significant impact on the energy efficiency of buildings. Little work has been done to quantify these losses in apartment buildings. In this paper we will discuss field measurements made on four forced air heating systems to evaluate the duct system energy losses to unconditioned basements. The apartments were heated by natural gas furnaces located in the basements. The systems had bare sheet metal ductwork exposed to the basement conditions. The pre- retrofit measurements were made on the systems after sealing large easily visible leaks. The post-retrofit measurements were made after wrapping the ducts in foil backed glass fiber insulation and additional leak sealing. Only the sections of duct exposed to the basement were retrofitted because only these sections were accessible. This study examines the potential energy savings for this type of limited retrofit. The energy losses were separated into leakage and conduction terms. Leakage measurements were made using register flowhood techniques. Conduction losses were estimated by measuring temperatures in the plenums and at the registers. Analysis of the measurements has shown typical reduction in leakage flow due to duct sealing of about 40%. The reduction in leakage translated into a reduction in energy consumption of about 10%.

Stetiu, C.; Feustel, H. E. "Development of a Model to Simulate the Performance of Hydronic Radiant Cooling Ceilings." 1995. LBL-36636.

2.5. Ventilation and Air Cleaning

Shendell, D.G; Prill,R.; Fisk, W.J.; Apte, M.G.; Blake, D.; Faulkner, D. "Associations between classroom CO2 concentrations and student attendance in Washington and Idaho." Accepted for publication in Indoor Air 2004. 2004. LBNL-54413 .

Abstract. Student attendance in American public schools is a critical factor in securing limited operational funding. Student and teacher attendance influence academic performance. Limited data exist on indoor air and environmental quality (IEQ) in schools, and how IEQ affects attendance, health, or performance. This study explored the association of student absence with measures of indoor minus outdoor carbon dioxide concentration (dCO2). Absence and dCO2 data were collected from 409 traditional and 25 portable classrooms from 22 schools located in six school districts in the states of Washington and Idaho. Study classrooms had individual heating, ventilation, and air conditioning (HVAC) systems, except two classrooms without mechanical ventilation. Classroom attributes, student attendance and school-level ethnicity, gender, and socioeconomic status (SES) were included in multivariate modeling. Forty-five percent of classrooms studied had short-term indoor CO2 concentrations above 1000 parts-per-million (ppm). A 1000 ppm increase in dCO2 was associated (p ¡ 0.05) with a 0.5% to 0.9% decrease in annual average daily attendance (ADA), corresponding to a relative 10% to 20% increase in student absence. Annual ADA was 2% higher (p ¡ 0.0001) in traditional than in portable classrooms.

Seppänen, O.; Fisk, W.J.; Faulkner, D. "Cost benefit analysis of the night-time ventilative cooling in office building." Proceedings of the Healthy Buildings 2003 Conference, Singapore, Volume 3, Pages 394-399, Healthy Buildings 2003, Inc., Singapore. 2003. LBNL-53191 .

Abstract. The indoor temperature can be controlled with different levels of accuracy depending on the building and its HVAC system. The purpose of this study was to evaluate the potential productivity benefits of improved temperature control, and to apply the information for a cost-benefit analyses of night-time ventilative cooling, which is a very energy efficient method of reducing indoor daytime temperatures. We analyzed the literature relating work performance with temperature, and found a general decrement in work performance when temperatures exceeded those associated with thermal neutrality. These studies included physiological modelling, performance of various tasks in laboratory experiments and measured productivity at work in real buildings. The studies indicate an average 2% decrement in work performance per degree oC temperature rise, when the temperature is above 25 oC. When we use this relationship to evaluate night- time ventilative cooling, the resulting benefit to cost ratio varies from 32 to 120.

Hodgson, A.T.; Faulkner, D.; Sullivan, D.P.; Dibartolomeo, D.L.; Russell, M.L.; Fisk, W.J. "Effect of Outside Air Ventilation Rate on Volatile Organic Compound Concentrations in a Call Center." Atmospheric Environment, Volume 37, Pages 5517-5528. 2003. LBNL-52497 .

Abstract. A study of the relationship between outside air ventilation rate and concentrations of volatile organic compounds (VOCs) generated indoors was conducted in a call center office building. The building, with two floors and a floor area of 4,600 m2, was located in the San Francisco Bay Area, CA. Ventilation rates were manipulated with the building's four air handling units (AHUs). VOC concentrations in the AHU returns were measured on seven days during a 13-week period. VOC emission factors were determined for individual zones on days when they were operating at near steady-state conditions. The emission factor data were subjected to principal component (PC) analysis to identify groups of co-varying compounds. Potential sources of the PC vectors were ascribed based on information from the literature supporting the associations. Two vectors with high loadings of compounds including formaldehyde, 2,2,4-trimethyl-1,3- pentanediol monoisobutyrate, decamethylcyclopentasiloxane (d5 siloxane), and isoprene likely identified occupant-related sources. One vector likely represented emissions from building materials. Another vector represented emissions of solvents from cleaning products. The relationships between indoor minus outdoor VOC

concentrations and ventilation rate were qualitatively examined for eight VOCs. Of these, acetaldehyde and hexanal, which were likely associated with material sources, and d5 siloxane exhibited general trends of higher concentrations at lower ventilation rates. For other compounds, the operation of the building and variations in pollutant generation and removal rates apparently combined to obscure the inverse relationship between VOC concentrations and ventilation. This result emphasizes the importance of utilizing source control measures, in addition to adequate ventilation, to limit concentrations of VOCs of concern in office buildings.

Fisk, W.J.; Faulkner, D.; Sullivan, D.P.; Delp, W.W. "Outdoor airflow into HVAC systems: An evaluation of measurement technologies." 2003. LBNL-53834 .

Abstract. During the last few years, new technologies have been introduced for measuring the flow rates of outdoor air (OA) into HVAC systems; however, an evaluation of these measurement technologies has not previously been published. This document describes a test system and protocols developed for controlled evaluation of these measurement technologies. The results of tests of three measurement technologies are also summarized. The test system and protocol were judged practical and very useful. The test results indicate that one measurement technology can measure OA flow rates with errors of 20% or less without a field-based calibration, as long as the OA velocities are sufficient to provide an accurately measurable pressure signal. The test results for a second measurement technology are similar; however, a difficult field-based calibration relating the OA flow rate with the pressure signal would be required to reduce errors below approximately 30%. The errors in OA flow rates measured with the third measurement technology, that uses six electronic airspeed sensors downstream of the OA inlet louver, exceeded 100%; however, these errors could be substantially reduced through a difficult field based calibration. The effects of wind on the accuracy of these measurement technologies still needs to be evaluated.

Fisk, W.J.; Faulkner, D.; Palonen, J.; Seppänen, O. "Performance and Costs of Particle Air Filtration in HVAC Supply Airstreams." HPAC Engineering, Volume 75, Pages 24-36. 2003. LBNL-53212 .

Abstract. This paper uses a model, and data on particle size distributions, filter efficiencies, and particle deposition rates to estimate the reductions in the indoor mass concentrations of particles attainable from use of filters in HVAC supply airstreams. Additionally, the energy and total costs of the filtration options are estimated. Predicted reductions in cat and dust-mite allergen concentrations range from 20% to 60%. Increasing filter efficiencies above approximately ASHRAE Dust Spot 65% (MERV 11) does not significantly reduce predicted indoor concentrations of these allergens. For environmental tobacco smoke particles and outdoor fine mode particles, calculations indicate that relatively large, e.g., 80%, decreases in indoor concentrations are attainable with practical filter efficiencies. Increasing the filter efficiency above ASHRAE Dust Spot 85% (MERV 13) results in only modest incremental decreases in concentrations. Energy costs and total costs do not always increase for higher efficiency filters. Total estimated filtration costs of $0.70 to $1.80 per person per month are insignificant relative to salaries, rent, or health insurance costs.

Faulkner, D.; Fisk, W.J.; Sullivan, D.P.; Lee, S.M. "Ventilation Efficiencies And Thermal Comfort Results Of A Desk-Edge-Mounted Task Ventilation System." Accepted for publication in Indoor Air 2003. 2003. LBNL-53798 .

Abstract. In chamber experiments, we investigated the ventilation effectiveness and thermal comfort of a task ventilation system with an air supply nozzle located underneath the front edge of a desk and directing air toward a heated mannequin or a human volunteer seated at the desk. The task ventilation system provided outside air, while another ventilation system provided additional space cooling but no outside air. Test variables included the vertical angle of air supply (-15o to 45o from horizontal), and the supply flow rate of (3.5 to 6.5 L s-1). Using the tracer gas step-up and step-down procedures, the measured air change effectiveness (i.e., exhaust air age divided by age of air in the breathing zone) in experiments with the mannequin ranged from 1.4 to 2.7 (median, 1.8), whereas with human subjects the air change effectiveness ranged from 1.3 to 2.3 (median, 1.6). The majority of the air change effectiveness values with the human subjects were less than values with the mannequin at comparable tests. Similarly, the tests run with supply air temperature equal

to the room air temperature had lower air change effectiveness values than comparable tests with the supply air temperature lower (5 o C) than the room air temperature. The change effectiveness values are higher than typically reported for commercially available task ventilation or displacement ventilation systems. Based on surveys completed by the subjects, operation of the task ventilation system did not cause thermal discomfort.

Alevantis, L.; Wagner, J.; Fisk, W.J.; Sullivan, D.P.; Faulkner, D. "Designing for Smoking Rooms." ASHRAE Journal, Volume 45, Pages 26-32. 2003. LBNL-53201 .

Abstract. No Abstract available.

Gundel, L.A.; Sullivan, D.P.; Katsapov, G.Y.; Fisk, W.J. "A Pilot Study Of Energy Efficient Air Cleaning For Ozone." 2002. LBNL-51836 .

Abstract. This report explores the feasibility of energy efficient low cost ozone removal from indoor air by examining carbon-based filtration options. Several candidate carbon-based materials and configurations were assessed by review of previous work and performance calculations. In addition, a laboratory pilot study was undertaken with the material that showed the most potential promise. This material was a commercially available filter that contained a thin layer of small activated carbon particles in a pleated configuration. For three months ozone (113 ? 13 ppm) in particle-filtered ambient air passed through the filter at a realistic ventilation system face velocity of 0.5 m s-1. Ozone was injected upstream of the filter, and its concentration was monitored continuously upstream and downstream of the filter, as well as in the incoming ambient air. Throughout the three-month period, continuous measurements were made of the ambient temperature and humidity, as well as flow rate and pressure drop through the filter. The ozone removal efficiency was initially 96% and remained at 50% or higher for two and a half months. The estimated ozone removal capacity, before the efficiency dropped below 50%, was 0.3 g ozone per gram carbon. The pressure drop of the air flowing through the ozone filter was 26 Pa. Based on the size, efficiency, measured lifetime, and pressure drop of the ozone filter, it appears that ozone air cleaning may be practical in commercial air handling systems.

Fisk, W.J.; Price, P.N.; Faulkner, D.; Sullivan, D.P.; Dibartolomeo, D.; Federspiel, C.; Liu, L.; Lahiff, M. "Worker productivity and ventilation rate in a call center: analyses of time-series data for a group of workers." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 790-795, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49356 .

Abstract. In previous studies, increased ventilation rates and reduced indoor carbon dioxide concentrations have been associated with improvements in health at work and increased performance in work-related tasks. Very few studies have assessed whether ventilation rates influence performance of real work. This paper describes part one of a two-part analysis from a productivity study performed in a call center operated by a health maintenance organization. Outside air ventilation rates were manipulated, indoor air temperatures, humidities, and carbon dioxide concentrations were monitored, and worker performance data for advice nurses, with 30-minute resolution, were analyzed via multivariate linear regression to look for an association of performance with building ventilation rate, or with indoor carbon dioxide concentration (which is related to ventilation rate per worker). Results suggest that the effect of ventilation rate on worker performance in this call center was very small (probably less than 1%) or nil, over most of the range of ventilation rate experienced during the study (roughly 12 L s-1 to 48 L s-1 per person). However, there is some evidence suggesting performance improvements of 2% or more when the ventilation rate per person is very high, as indicated by indoor CO2 concentrations exceeding outdoor concentrations by less than 75 ppm.

Fisk, WJ; Faulkner, D; Palonen, J; Seppänen, O. "Performance and cost of particle air filtration technologies." Indoor Air, Volume 12, Pages 223-234. 2002. LBNL-47833.

Abstract. This paper predicts the reductions in the indoor mass concentrations of particles attainable from use of filters in building supply airstreams and also from use of stand-alone fan-filter units. Filters with a wide efficiency range are considered. Predicted concentration reductions are

provided for indoor-generated particles containing dust mite and cat allergen, for environmental tobacco smoke particles, and for outdoor- air fine mode particles. Additionally, this paper uses a simple model and available data to estimate the energy and total costs of the filtration options. Predicted reductions in cat and dust-mite allergen concentrations range from 20% to 80%. To obtain substantial, e.g., 50%, reductions in indoor concentrations of these allergens, the rate of airflow through the filter must be at least a few indoor volumes per hour. Increasing filter efficiencies above approximately ASHRAE Dust Spot 65% does not significantly reduce predicted indoor concentrations of these allergens. For environmental tobacco smoke particles and outdoor fine mode particles, calculations indicate that relatively large, e.g., 80%, decreases in indoor concentrations are attainable with practical filter efficiencies and flow rates. Increasing the filter efficiency above ASHRAE 85% results in only modest predicted incremental decreases in indoor concentration. Energy costs and total costs can be similar for filtration using filters with a wide range of efficiency ratings. Total estimated filtration costs of approximately $0.70 to $1.80 per person per month are insignificant relative to salaries, rent, or health insurance costs.

Faulkner, D.; Fisk, W.J.; Sullivan, D.P.; Lee, S.M. "Ventilation efficiencies of a desk-edge-mounted task ventilation system." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 4, Pages 1060-1065, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49939 .

Abstract. In chamber experiments, we investigated the effectiveness of a task ventilation system with an air supply nozzle located underneath the front edge of a desk and directing air toward a heated mannequin seated at the desk. The task ventilation system provided outside air, while another ventilation system provided additional space cooling but no outside air. Test variables included the vertical angle of air supply (-15o to 45o from horizontal), and the supply flow rate of (3.5 to 6.5 L s-1). Using the tracer gas step-up and step- down procedures, the measured air change effectiveness (i.e., exhaust air age divided by age of air at the mannequin's face) ranged from 1.4 to 2.7, which is higher than typically reported for commercially available task ventilation or displacement ventilation systems.

Apte, M.G.; Delp, W.W.; Diamond, R.C.; Hodgson, A.T.; Kumar, S.; Shendell, D.G.; Sullivan, D.P.; Fisk, W.J. "Report on HVAC Option Selections for a Relocatable Classroom Energy and Indoor Environmental Quality Field Study." 2001. LBNL-49026 .

Fisk, W.J.; Sullivan, D.; Mendell, M. "Particle Concentrations in an Air-Conditioned Office Building with Normal and High Efficiency Filtration." Proceedings of the Indoor Air '99, Edinburgh, Scotland, Volume 4, Pages 19-24, Construction Research Communications, Ltd., London. 1999. LBNL-43174.

Faulkner, D.; Fisk, W.J.; Sullivan, D.; Wyon, D.P. "Ventilation Efficiencies of Desk-Mounted Task/Ambient Conditioning Systems." Proceedings of the Indoor Air '99 Conference, Edinburgh, Scotland, Volume 9, Pages 273-281, Construction Research Communications, Ltd., London. 1999. LBNL-42700 .

Faulkner, D.; Fisk, W.J.; Sullivan, D; Wyon, D.P. "Ventilation Efficiencies of Task Air Conditioning Systems With Desk-Mounted Air Supplies." Proceedings of the Indoor Air '99, Edinburgh, Scotland, Volume 2, Pages 356-361, Construction Research Communications. Ltd., London. 1999. LBNL-42597 .

Fisk, W.J.; de Almeida, A.T. "Sensor based demand controlled ventilation: a review." Energy and Buildings, Volume 29, Pages 35-44. 1998. LBNL-41698.

Faulkner, D. F.; Fisk, W.J.; Sullivan, D.P.; Thomas, J.M. "Characterizing Building Ventilation with the Pollutant Concentration Index: Results from Field Studies." Proceedings of the ASHRAE IAQ and Energy 1998, Pages 27-35, ASHRAE, Atlanta, GA. 1998. LBNL-40223.

Fisk, W.J.; Faulkner, D.; Sullivan, D.P.; Bauman, F. "Air Change Effectiveness and Pollutant Removal Efficiency During Adverse Mixing Conditions." Indoor Air, Volume 7, Pages 55-63. 1997. LBNL-40292.

Faulkner, D.; Fisk, W.J.; Walton, J.T. "Energy Savings in Cleanrooms from Demand-Controlled Filtration." Journal of the Institute of Environmental Sciences, Volume 39, Pages 21-27. 1996. LBNL-38869.

Faulkner, D.; Fisk, W.J.; Sullivan, D.P. "Indoor Airflow and Pollutant Removal in a Room With Floor-Based Task Ventilation: Results of Additional Experiments." Building and Environment, Volume 30, Pages 323-332. 1995. LBL-36131.

2.6. Volatile Organic Compounds

Hodgson, A.T.; Shendell, D.G.; Fisk, W.J.; Apte, M.G. "Comparison of predicted and derived measures of volatile organic compounds inside four relocatable classrooms die to identified interior finish sources." Accepted for publication in Indoor Air. 2004. LBNL-52520 .

Abstract. Indoor exposures to toxic and odorous volatile organic compounds (VOCs) are of general concern. Recently, VOCs in portable or relocatable classrooms (RCs) have received particular attention. However, very little was known about indoor environmental quality (IEQ) and the sources, composition, and indoor concentrations of VOCs in RCs. This project task focused on developing and demonstrating a process for selecting interior finish materials for RCs that have relatively low impacts with respect to their emissions of toxic and odorous VOCs. This task was part of a larger project to demonstrate the potential for simultaneous improvements in IEQ and energy efficiency in four new RCs equipped both with a continuously ventilating advanced heating, ventilating, and air conditioning system (HVAC) and a standard HVAC system. These HVACs were operated on alternate weeks. One RC per pair was constructed with standard interior finish materials, and the other included alternate interior materials identified in our prior laboratory study to have low VOC emissions. The RCs were sited in side-by-side pairs at two elementary schools in distinct northern California climate zones. Classroom VOC emission rates (mg hr-1) and concentrations were predicted based on VOC emission factors (μg m-2 hr-1) measured for individual materials in the laboratory, the quantities of installed materials and design ventilation rates. Predicted emission rates were compared to values derived from classroom measurements of VOC concentrations and ventilation rates made at pre-occupancy, eight weeks, and 27 weeks. Predicted concentrations were compared to measured integrated VOC indoor minus outdoor concentrations during school hours in the fall cooling season with the advanced HVAC operated. These measured concentrations also were compared between standard and material-modified RCs. Our combined laboratory and field process proved effective by correctly predicting that IEQ impacts of material VOC emissions would be minor when RCs were ventilated at or above code-minimum requirements. Assuming code-minimum ventilation rates are maintained, the benefits attributable to the use of alternate interior finish materials in RC's constructed by the manufacturer associated with this study are small, implying that it is not imperative to use such alternative finishing materials. However, it is essential to avoid materials that can degrade IEQ, and the results of this study demonstrate that laboratory-based material testing combined with modeling and field validation can help to achieve that aim.

Hodgson, A.T.; Faulkner, D.; Sullivan, D.P.; Dibartolomeo, D.L.; Russell, M.L.; Fisk, W.J. "Effect of Outside Air Ventilation Rate on Volatile Organic Compound Concentrations in a Call Center." Atmospheric Environment, Volume 37, Pages 5517-5528. 2003. LBNL-52497 .

Abstract. A study of the relationship between outside air ventilation rate and concentrations of volatile organic compounds (VOCs) generated indoors was conducted in a call center office building. The building, with two floors and a floor area of 4,600 m2, was located in the San Francisco Bay Area, CA. Ventilation rates were manipulated with the building's four air handling units (AHUs). VOC concentrations in the AHU returns were measured on seven days during a 13-week period. VOC emission factors were determined for individual zones on days when they were operating at near steady-state conditions. The emission factor data were subjected to principal component (PC) analysis to identify groups of co-varying compounds. Potential sources of the PC vectors were ascribed based on information from the literature supporting the associations. Two vectors with high loadings of compounds including formaldehyde, 2,2,4-trimethyl-1,3- pentanediol monoisobutyrate, decamethylcyclopentasiloxane (d5 siloxane), and isoprene likely identified occupant-related sources. One vector likely represented emissions from building materials. Another vector represented emissions of solvents from cleaning products. The relationships between indoor minus outdoor VOC concentrations and ventilation rate were qualitatively examined for eight VOCs. Of these, acetalde-

hyde and hexanal, which were likely associated with material sources, and d5 siloxane exhibited general trends of higher concentrations at lower ventilation rates. For other compounds, the operation of the building and variations in pollutant generation and removal rates apparently combined to obscure the inverse relationship between VOC concentrations and ventilation. This result emphasizes the importance of utilizing source control measures, in addition to adequate ventilation, to limit concentrations of VOCs of concern in office buildings.

Hodgson, A.T.; Levin, H. "Volatile organic compounds in indoor air: A review of concentrations measured in North America since 1990." Accepted for publication in Atmospheric Environment. 2003. LBNL-51715 .

Abstract. Central tendency and upper limit concentrations of volatile organic compounds (VOCs) measured in indoor air are summarized and reviewed. Data were obtained from published cross-sectional studies of residential and office buildings conducted in North America from 1990 through the present. VOC concentrations in existing residences reported in 12 studies comprise the majority of the data set. Central tendency and maximum concentrations are compared between new and existing residences and between existing residences and office buildings. Historical changes in indoor VOC concentrations since the Clean Air Act Amendments of 1990 are explored by comparing the current data set with two published reviews of previous data obtained primarily in the 1980s. These historical comparisons suggest average indoor concentrations of some toxic air contaminants, such as 1,1,1-trichloroethane have decreased.

Hodgson, A.T.; Levin, H. "Classification of measured indoor volatile organic compounds based on noncancer health and comfort considerations." To be submitted to Atmospheric Environment. 2003. LBNL-53308 .

Abstract. Building occupants are exposed to complex mixtures of air pollutants including many volatile organic compounds (VOCs). A recent review summarized the central tendency and upper limit indoor VOC concentrations measured in North American residences and office buildings since 1990. Although this database is limited in many respects, it serves as a useful starting point for evaluating the potential health and comfort effects of indoor VOC exposures. Excluding cancer and birth defects, the primary concern is chronic inhalation exposure to toxicants that can cause serious health problems. Additionally, building occupants react to the quality of indoor air through their sensory perceptions and frequently experience unpleasant odors and irritation of the eyes and upper respiratory tract. In this paper, we conduct a simple screening-level assessment of indoor VOC concentrations. We compare measured VOC concentrations to published odor thresholds, sensory irritation levels derived for the general population, and noncancer chronic health guidelines. Hazard quotients are individually calculated for these three effects by dividing maximum or derived 95th percentile VOC concentrations by our selected best estimates of guidance levels for the general population. These results provide a basis for broadly classifying commonly encountered VOCs into groups according to the likelihood that they will produce effects among building occupants. This methodology shows that only a small number of the more than 100 reported VOCs exceed levels that are likely to be of concern with respect to the health and comfort endpoints considered. Although data is lacking for a number of odorous compounds potentially present in buildings, the results indicate that carboxylic acids, higher molecular weight aldehydes and less volatile aromatic hydrocarbons are most likely to be perceived by olfaction and that there is more probability of detection in residences than in offices. Sensory irritation levels were approached or exceed by only a very small number of relatively potent, reactive VOCs. Of these, acrolein was by far the most potent irritant. Although more detailed consideration of the underlying toxicological data is needed, the results suggest that only a small number of commonly measured VOCs, when considered singly, are likely to produce serious irreversible health effects not associated with cancer. These compounds include lower molecular weight aldehydes, and several aromatic hydrocarbons. Again, acrolein stands out as the most potent compound. Based on these results, we recommend that studies to characterize indoor VOC concentrations and exposures focus their resources on compounds that are most likely to impact occupants as determined by the study objectives. For a very few compounds, such as acrolein and formaldehyde, the evidence based on sensory irritation and chronic toxicity appears sufficient to warrant efforts to reduce and control sources of these compounds in buildings.

Zhao, D; Little, J.C.; Hodgson, A.T. "Modeling the Reversible Sink Effect in Response to Transient Contaminant Sources." Indoor Air, Volume 12, Pages 184-190. 2002. LBNL-47095 .

Abstract. A physically based diffusion model is used to evaluate the sink effect of diffusion-controlled indoor materials and to predict the transient contaminant concentration in indoor air in response to several time-varying contaminant sources. For simplicity, it is assumed that the predominant indoor material is a homogeneous slab, initially free of contaminant, and that the air within the room is well mixed. The model enables transient volatile organic compound (VOC) concentrations to be predicted based on the material/air partition coefficient (K) and the material-phase diffusion coefficient (D) of the sink. Model predictions are made for four scenarios, each mimicking a realistic situation in a building. Styrene, phenol, and naphthalene are used as representative VOCs. A styrene butadiene rubber (SBR) backed carpet, vinyl flooring (VF), and a polyurethane foam (PUF) carpet cushion are considered as typical indoor sinks. In scenarios involving a sinusoidal VOC input and a double exponential decaying input, the model predicts that the sink has a modest impact for SBR/styrene, but that the effect increases for VF/phenol and PUF/naphthalene. In contrast, for an episodic chemical spill, SBR is predicted to reduce the peak styrene concentration considerably. A parametric study reveals that for systems involving a high equilibrium factor (K), the kinetic factor (D) will govern the shape of the resulting gas-phase concentration profile. On the other hand, for systems with a relaxed mass transfer resistance, K will dominate the profile.

Shendell, D.G.; Hodgson, A.T.; Lee, S.M; Apte, M.G.; Sullivan, D.P.; Hotchi, T.; Fisk, W.J. "VOCs in New Relocatable Classrooms: Assessment of School-Day Exposures Comparing Interior Finish Materials and HVAC Systems." Epidemiology, Volume 13, Pages S143. 2002. Abstract (no LBNL number).

Abstract. The prevalence of relocatable classrooms (RCs) at schools is rising due to initiatives to reduce K-3 class size, and limited capital resources. Concerns regarding inadequate ventilation and indoor air quality in RCs have been raised. Since students and teachers spend the majority of a 7-8 hour school day inside classrooms, indoor contaminant concentrations are assumed to drive personal school-day exposures. We conducted a demonstration project in new relocatable classrooms (RCs) during the 2001-02 school year to address these issues. The benefits of upgrades including an energy efficient heating, ventilation, and air conditioning (HVAC) system and alternate interior finish materials were investigated. One specific goal was to demonstrate that improved ventilation coupled with source reduction could lower indoor concentrations of toxic and odorous volatile organic compounds (VOCs), including formaldehyde and acetaldehyde. Four new 24' x 40' (960 ft2) RCs were constructed and sited in pairs at an elementary school campus in each of two participant school districts (SD) in Northern California. Each RC was equipped with a standard HVAC system with intermittent 25-50% outdoor air ventilation and an energy-efficient advanced system providing continuous 100% ventilation (15 cfm/occupant). Alternate carpets, wall panels, and ceiling panels were installed in two classrooms – one in each pair – based on the results of a laboratory study of VOC emissions from standard and alternate materials. The two HVAC systems were operated on alternate weeks. School day-integrated air samples were collected indoors and outdoors mid-week during eight and nine weeks in the cooling (fall) and heating (winter) seasons, respectively. VOCs were collected on sorbent media and analyzed by thermal desorption GC/MS. Aldehydes were collected on DNPH treated silica gel cartridges and analyzed by HPLC. The effects of material selection on VOC concentrations were evaluated by emissions studies conducted prior to and after the first eight weeks of occupancy and by a comparison of occupied-hour classroom concentrations with the advanced HVAC operational. Slightly lower phenol and 1-methyl-2-pyrrolidinone concentrations in source-modified RCs were attributed to the alternate wall panel. Slightly lower formaldehyde concentrations in these RCs were attributed to the lower- emitting ceiling panels. At one school, teaching materials brought in after the school year began were discovered to be formaldehyde sources. Across SD and RCs in the cooling season, mean concentrations of formaldehyde were 14.1 +/- 6.6 and 30.4 +/- 6.9 μg m-3 during advanced and standard HVAC system operation, respectively. Likewise, acetaldehyde mean concentrations were 6.9 +/- 4.7 and 13.7 +/- 3.7 μg m-3, respectively. Similar reductions were observed for toluene and phenol. Results suggest improved continuous ventilation provided by the advanced HVAC outweighed source reduction as a VOC control measure in these new RCs.

Hodgson, A.T.; Faulkner, D.; Sullivan, D.P.; DiBartolomeo, D.L.; Russell, M.L.; Fisk, W.J. "Effect of outside air ventilation rate on VOC concentrations and emissions in a call center." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 2, Pages 168-173, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49535 .

Abstract. A study of the relationship between outside air ventilation rate and concentrations of VOCs generated indoors was conducted in a call center. Ventilation rates were manipulated in the building's four air handling units (AHUs). Concentrations of VOCs in the AHU returns were measured on 7 days during a 13- week period. Indoor minus outdoor concentrations and emission factors were calculated. The emission factor data was subjected to principal component analysis to identify groups of co-varying compounds based on source type. One vector represented emissions of solvents from cleaning products. Another vector identified occupant sources. Direct relationships between ventilation rate and concentrations were not observed for most of the abundant VOCs. This result emphasizes the importance of source control measures for limiting VOC concentrations in buildings.

Hodgson, A.T.; Apte, M.G.; Shendell, D.G.; Beal, D.; McIlvaine, J.E.R. "Implementation of VOC Source Reduction Practices in a Manufactured House and in School Classrooms." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 3, Pages 576-581, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49536 .

Abstract. Detailed studies of a new manufactured house and four new industrialized relocatable school classrooms were conducted to determine the emission sources of formaldehyde and other VOCs and to identify and implement source reduction practices. Procedures were developed to generate VOC emission factors that allowed reasonably accurate predictions of indoor air VOC concentrations. Based on the identified sources of formaldehyde and other aldehydes, practices were developed to reduce the concentrations of these compounds in new house construction. An alternate ceiling panel reduced formaldehyde concentrations in the classrooms. Overall, the classrooms had relatively low VOC concentrations.

Hodgson, A.T.; Fisk, W.J.; Shendell, D.G; Apte, M.G. "Predicted concentrations in new relocatable classrooms of volatile organic compounds emitted from standard and alternate interior finish materials." 2001. LBNL-48490 .

Hodgson, A.T. "Common Indoor Sources of Volatile Organic Compounds: Emission Rates and Techniques for Reducing Consumer Exposures." 1999. LBNL-42402.

Levin, H.; Hodgson, A.T. "Screening and Selecting Building Materials and Products Based on Their Emissions of Volatile Organic Compounds (VOCs)." ASTM STP 1287, Characterizing Sources of Indoor Air Pollution and Related Sink Effects, Pages 376-391, American Society for Testing and Materials, Philadelphia, PA. 1996.

Mahanama, K. R. R.; Hodgson, A. T. "An Improved Inpregnated-filter Method for Measuring Low-level Concentrations fo Toluene Diiscoyanates in Air." 1995.

3. Residential Building Energy and Environmental Quality

3.1. Energy Retrofits and Diagnostics

Walker, I.S. "Best practices guide for residential HVAC retrofits." 2004. LBNL-53592.

Abstract. This best practices guide for residential HVAC system retrofits is aimed at contractors who want guidance on delivering energy efficient, cost effective and innovative products. It has been developed around the idea of having packages of changes to the building HVAC system and building envelope that are climate and house construction dependent. These packages include materials, procedures and equipment and are designed to remove some of the guesswork from a builder, contractor, installer or homeowner decisions about how best to carry out HVAC changes. The packages are not meant to be taken as rigid requirements - instead they are systems engineered guidelines that form the basis for energy efficient retrofits. Similar approaches have been taken previously for new construction to develop extremely energy efficient homes that are comfortable safe and durable, and often cost less than standard construction. This is best epitomized by the Building America program whose partners have built thousands of residences throughout the U.S. using these principles. The differences between retrofitting and new construction tend to limit the changes one can make to a building, so these packages rely on relatively simple and non-intrusive technologies and techniques. The retrofits also focus on changes to a building that will give many years of service to the occupants.

Another key aspect of these best practices is that we need to know how a house is working so that we know what parts have the potential for improvement. To do this we have put together a set of diagnostic tools that combine physical measurements and checklists/questionnaires. The measured test results, observations and homeowner answers to questions are used to direct us towards the best retrofits applicable to each individual house. The retrofits will depend on the current condition of the building envelope and HVAC system, the local climate, the construction methods used for the house, and the presence of various energy saving systems (e.g., a Heat Recovery Ventilator) and/or materials. This is just like a doctor referring a patient for blood tests or x-rays before actually performing surgery. This way the doctor can be sure that he does the right thing. To take this analogy further - we can borrow from the medical profession and say that the first thought when retrofitting a house is to do no harm, i.e., do not make changes that could make the house worse to live in.

McWilliams, J.; Walker, I.S. "A systems approach to retrofiting residential HVAC systems." Submitted to 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy, Washington, DC. 2004. LBNL-54696 .

Abstract. A Best Practices Guide for retrofitting residential HVAC systems has recently been completed by DOE. The guide uses diagnostics and checklists to guide the user to specific retrofit packages that maximize retrofit energy savings, comfort and safety potential. The guide uses a systems approach to retrofitting where the interaction of different building components is considered throughout the retrofit selection process. For example, added building envelope insulation reduces building loads so that smaller capacity HVAC systems can be used. In this study, several houses were surveyed using the Best Practices Guide and a single house was selected for retrofitting. The objectives were to demonstrate how a successful system-wide retrofit can be carried out and to provide feedback to improve the guide. Because it represents a departure from current practice, a key aspect of this study was to investigate the interactions with contractors and code officials who are unfamiliar with the systems approach. The study found that the major barrier to the systems approach in retrofits was in changing the working practices of contractors and code officials.

Matson, N.; Sherman, M. "Why We Ventilate Our Houses An Historical Look." Submitted to 2004 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August 22-27, 2004, American Council for an Energy Efficient Economy, Washington, DC. 2004. LBNL-55107 .

Abstract. The knowledge of how to ventilate buildings, and how much ventilation is necessary for human health and comfort, has evolved over centuries of trial and error. Humans and animals

have developed successful solutions to the problems of regulating temperature and removing air pollutants through the use of ventilation. These solutions include ingenious construction methods, such as engineered passive ventilation (termite mounds and passive stacks), mechanical means (wing-powered, fans), and an evolving effort to identify problems and develop solutions. Ventilation can do more than help prevent building occupants from getting sick; it can provide an improved indoor environment. Codes and standards provide minimum legal requirements for ventilation, but the need for ventilation goes beyond code minima. In this paper we will look at indoor air pollutant sources over time, the evolution of ventilation strategies, current residential ventilation codes and standards (e.g., recently approved ASHRAE Standard 62.2), and briefly discuss ways in which we can go beyond the standards to optimize residential ventilation, reduce indoor air quality problems, and provide corresponding social and economic benefit.

Wray, Craig; Walker, Iain; Sherman, Max. "Guidelines for Residential Commissioning." 2003. LBNL-48767 .

Abstract. This guide is the culmination of a 30-month project that began in September 1999. The ultimate objective of the project is to increase the number of houses that undergo commissioning, which will improve the quality, comfort, and safety of homes for California citizens. The project goal is to lay the groundwork for a residential commissioning industry in California focused on end-use energy and non-energy issues. As such, we intend this guide to e a beginning and not an end. Our intent is that the guide will lead to the programmatic integration of commissioning with other building industry processes, which in turn will provide more value to a single site visit for people such as home energy auditors and raters, home inspectors, and building performance contractors.

Walker, I.S.; Sherman, M.H. "Heat Recovery in Building Envelopes." 2003. LBNL 53484.

Abstract. Infiltration has traditionally been assumed to contribute to the energy load of a building by an amount equal to the product of the infiltration flow rate and the enthalpy difference between inside and outside. Some studies have indicated that application of such a simple formula may produce an unreasonably high contribution because of heat recovery within the building envelope. The major objective of this study was to provide an improved prediction of the energy load due to infiltration by introducing a correction factor that multiplies the expression for the conventional load. This paper discusses simplified analytical modeling and CFD simulations that examine infiltration heat recovery (IHR) in an attempt to quantify the magnitude of this effect for typical building envelopes. For comparison, we will also briefly examine the results of some full-scale field measurements IHR based on infiltration rates and energy use in real buildings. The results of this work showed that for houses with insulated walls the heat recovery is negligible due to the small fraction of the envelope that participates in heat exchange with the infiltrating air. However; there is the potential for IHR to have a significant effect for higher participation dynamic walls/ceilings or uninsulated walls. This result implies that the existing methods for evaluating infiltration related building loads provide adequate results for typical buildings.

Walker, I.S.; McWilliams, J.A.; Konopacki., S.J. "Case Study Field Evaluation of a Systems Approach to Retrofitting a Residential HVAC System." 2003. LBNL-53444 .

Abstract. This case study focusing on a residence in northern California was undertaken as a demonstration of the potential of a systems approach to HVAC retrofits. The systems approach means that other retrofits that can affect the HVAC system are also considered. For example, added building envelope insulation reduces building loads so that smaller capacity HVAC system can be used. Secondly, we wanted to examine the practical issues and interactions with contractors and code officials required to accomplish the systems approach because it represents a departure from current practice. We identified problems in the processes of communication and installation of the retrofit that led to compromises in the final energy efficiency of the HVAC system. These issues must be overcome in order for HVAC retrofits to deliver the increased performance that they promise. The experience gained in this case study was used to optimize best practices guidelines for contractors (Walker 2003) that include building diagnostics and checklists as tools to assist in ensuring the energy efficiency of "house as a system" HVAC retrofits. The best practices guidelines

proved to be an excellent tool for evaluating the eight existing homes in this study, and we received positive feedback from many potential users who reviewed and used them. In addition, we were able to substantially improve the energy efficiency of the retrofitted case study house by adding envelope insulation, a more efficient furnace and air conditioner, an economizer and by reducing duct leakage.

Sherman, M.H.; Walker, I.S.; Wray, C.P. "Instrumented home energy rating and commissioning." 2003. LBNL-52216 .

Abstract. Currently, houses do not perform optimally or even as many codes and forecasts predict, largely because they are field assembled and there is no consistent process to identify deficiencies or to correct them. Solving this problem requires field performance evaluations using appropriate and agreed upon procedures in the form of a new process called residential commissioning. The purpose of this project is to develop and document these procedures and to demonstrate the value that applying them could provide in both new and existing California houses. This project has four specific objectives: to develop metrics and diagnostics for assessing house performance, to provide information on the potential benefits of commissioning using a whole-house approach, to develop programmatic guidelines for commissioning, and to conduct outreach efforts to transfer project results to industry stakeholders. The primary outcomes from this project are the development of residential commissioning guidelines and the analytical confirmation that there are significant potential benefits associated with commissioning California houses, particularly existing ones. In addition, we have made substantial advances in understanding the accuracy and usability of diagnostics for commissioning houses. In some cases, we have been able to work with equipment manufacturers to improve these aspects of their diagnostic tools. These outcomes provide a solid foundation on which to build a residential commissioning program in California. We expect that a concerted effort will be necessary to integrate such a program with existing building industry efforts and to demonstrate its use in the field.

Wray, C.P.; Walker, I.S.; Sherman, M.H. "Accuracy of flow hoods in residential applications." Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, California, Volume 1, Pages 339-350, American Council for an Energy Efficient Economy, Washington, DC. 2002. LBNL-49697 .

Abstract. To assess whether houses can meet performance expectations, the new practice of residential commissioning will likely use flow hoods to measure supply and return grille airflows in HVAC systems. Depending on hood accuracy, these measurements can be used to determine if individual rooms receive adequate airflow for heating and cooling, to determine flow imbalances between different building spaces, to estimate total air handler flow and supply/return imbalances, and to assess duct air leakage. This paper discusses these flow hood applications and the accuracy requirements in each case. Laboratory tests of several residential flow hoods showed that these hoods can be inadequate to measure flows in residential systems. Potential errors are about 20% to 30% of measured flow, due to poor calibrations, sensitivity to grille flow non-uniformities, and flow changes from added flow resistance. Active flow hoods equipped with measurement devices that are insensitive to grille airflow patterns have an order of magnitude less error, and are more reliable and consistent in most cases. Our tests also show that current calibration procedures for flow hoods do not account for field application problems. As a result, a new standard for flow hood calibration needs to be developed, along with a new measurement standard to address field use of flow hoods. Lastly, field evaluation of a selection of flow hoods showed that it is possible to obtain reasonable results using some flow hoods if the field tests are carefully done, the grilles are appropriate, and grille location does not restrict flow hood placement.

Wray, C.P.; Walker, I.S.; Siegel, J.A.; Sherman, M.H. "Practical Diagnostics for Evaluating Residential Commissioning Metrics." 2002. LBNL-45959 .

Abstract. In this report, we describe what residential commissioning is, its characteristic elements, and how one might structure its process. Our intent in this discussion is to formulate and clarify these issues, but is largely preliminary because such a practice does not yet exist. Subsequent sections of the report describe metrics one can use in residential commissioning, along with the consolidated set of 24 practical diagnostics that the building industry can use now to evaluate them.

Our discussion in the main body of this report is limited to existing diagnostics in areas of particular concern with significant interactions: envelope and HVAC systems. These areas include insulation quality, windows, airtightness, envelope moisture, fan and duct system airflows, duct leakage, cooling equipment charge, and combustion appliance backdrafting with spillage. Where possible, we also discuss the accuracy and usability of diagnostics, based on recent laboratory work and field studies by LBNL staff and others in more than 100 houses. These studies concentrate on evaluating diagnostics in the following four areas: the DeltaQ duct leakage test, air-handler airflow tests, supply and return grille airflow tests, and refrigerant charge tests. In addition, where possible, we identify the costs to purchase diagnostic equipment and the amount of time required to conduct the diagnostics.

Siegel, J.; Walker, I.S.; Sherman, M.H. "Dirty air conditioners: Energy implications of coil fouling." Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy, Washington, DC. 2002. LBNL-49757 .

Abstract. Residential air conditioning is responsible for a substantial amount of peak electrical demand and energy consumption throughout most of the United States. Coil fouling, the deposition of indoor dusts and other particulate matter on evaporator heat exchangers, increases system pressure drop and, correspondingly, decreases system air flow and air conditioner performance. In this paper, we apply experimental and simulation results describing particle deposition on evaporator coils as well as research about indoor particle and dust concentrations to determine coil fouling rates. The results suggest that typical coils foul enough to double evaporator pressure drop in 7 – 11 years, much sooner than the expected 15 – 30 year life time for an evaporator coil. The most important parameters in determining coil fouling times are the efficiency of the filter and indoor particle concentrations, although filter bypass and duct and coil design are important as well. The reduced air flows that result from coil fouling cause typical efficiency and capacity degradations of less than 5 %, however they can be much greater for marginal systems or extreme conditions. These energy issues, as well as possible indoor air quality issues resulting from fouling by biological aerosols, suggest that regular coil cleaning and the elimination of filter bypass should be an important part of residential air conditioning commissioning and maintenance practices.

Siegel, J.A.; Wray, C.P. "An Evaluation of Superheat-Based Refrigerant Charge Diagnostics for Residential Cooling Systems." ASHRAE Transactions, Volume 108. 2002. LBNL-47476 .

Abstract. Although refrigerant charge has an important influence on the performance of residential cooling systems with fixed orifice metering devices, there has been little research to quantify the effects of incorrect charge or design new diagnostics for evaluating charge level. The most common diagnostic for charge level in these systems is the superheat test. In this paper, we examine three superheat technologies/techniques. Two of the diagnostics are appropriate for detecting incorrect charge; one is not. Additionally, measurements at four houses indicate that it is important to measure the condenser air entering temperature with a high degree of accuracy. Measurement of the wet bulb temperature in the return plenum and suction line temperature are equally important, but seemingly easier then measuring the condenser air temperature, as several measurement technologies yielded similar results for these quantities. The importance of refrigerant charge to energy use and capacity of residential cooling systems, the limitations of the superheat test, and the variations in the test method results and interfaces necessitate the development of a standard method or methods to determine refrigerant charge level.

Matson, N.E.; Wray, C.P.; Walker, I.S.; Sherman, M.H. "Potential Benefits of Commissioning California Homes." 2002. LBNL-48258 .

Abstract. No Abstract Available

Diamond, Rick. "What might U.S. homes and workplaces be like in the year 2020–and what are the implications for energy use?." 2002. LBNL-50184 .

Abstract. Can lifestyle-based scenarios provide insight into the nature of energy use in our future buildings? Participants in a design charrette brainstormed ideas about the future of US homes and workplaces. The teams started from several descriptions of daily lifestyles, and developed specific

building characteristics as the place settings for these narratives. In addition to the characterization of the physical environment, we also speculate as to the forces that would be influential in making these changes. Further reflection was made on the possible unintended consequences of these changes. The rationale for this exercise was to broaden the discussion on future energy use by looking at future scenarios in the context of everyday life.

Wray, C.P.; Sherman, M.H. "Residential Commissioning to Assess Envelope and HVAC System Performance." Proceedings of the ASHRAE/DOE/BTECC Thermal Performance of Exterior Envelopes of Whole Buildings VIII, Clearwater Beach, FL, ASHRAE, Atlanta, GA. 2001. LBNL-47412 .

Abstract. Residential commissioning is a new procedure to ensure that a house can perform optimally or at least meet basic safety, health, comfort, and energy intents. Many procedural elements, such as visual inspection and functional performance diagnostics, already exist in a fragmented environment. Most can be integrated into new industry guidelines for testing and tuning system performance in new and existing houses. This paper describes a consolidated set of practical diagnostics that can be used now to commission envelope and HVAC system performance. Where possible, we discuss the accuracy and usability of available diagnostics, based on recent laboratory work and field studies. We also describe areas in need of research and development, such as practical field diagnostics for envelope thermal conductance and combustion safety.

Wray, C.P.; Piette, M.A.; Sherman, M.H.; Levinson, R.M.; Matson, N.E.; Driscoll, D.A.; McWilliams, J.A..; Xu, T.T.; Delp, W.W. "Residential Commissioning: A Review of Related Literature." 2000. LBNL-44535 .

Abstract. The literature review reported here is the first step in a larger 30 month-long project that will lay the groundwork for a residential commissioning industry in California focused on end-use energy and non- energy issues. The intent of the review is to facilitate access to existing literature related to residential commissioning. Emphasis is placed on reviewing documents published over the past 20 years, which represents the period of time over which building commissioning and closely related issues have been actively reported. This report discusses the status of commercial building commissioning and compares it with residential commissioning. Based on an extensive review of 469 readily available documents, it summarizes existing metrics, diagnostics, and norms for all building types that are relevant for evaluating, tuning, and retrofitting various aspects of new and existing houses. The relevant areas of concern for California houses are: Building Envelope, Cooling Equipment and Heat Pumps, Air Distribution Systems, Indoor Air Quality, Combustion Appliances, Controls, and Other Electrical Appliances. There is a substantial amount of useful information in the literature about metrics, diagnostics, and norms that are relevant to residential commissioning. However, there are also some significant gaps. This report concludes by highlighting gaps in existing knowledge that require further research and development. Areas in particular need of work include: metrics, diagnostics, and norms for thermal mass and moisture-damage susceptibility; diagnostics for steady-state capacity and efficiency, as well as refrigerant charge level, for cooling equipment and heat pumps; diagnostics and norms for ventilation effectiveness and efficiency; diagnostics to evaluate the potential for backdrafting and combustion gas spillage; and metrics, diagnostics, and norms for controls and other electrical appliances.

Salsbury, T.I.; Diamond, R.C. "Performance validation and energy analysis of HVAC systems using simulation." Energy & Buildings, Volume 32, Pages 5-17. 2000. LBNL-43638 .

Diamond, R.C. "An Overview of the U.S. Building Sector." Chapter 6 in Indoor Air Quality Handbook, McGraw Hill, New York. 2000. LBNL-43640 .

Diamond, R.C.; Moezzi, M. "Revealing myths about people, energy and buildings." Proceedings of the ACEEE 2000 Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 8, Pages 65-77, American Council for an Energy Efficient Economy, Washington, DC. 2000. LBNL-45862.

Salsbury, T.I.; Diamond, R.C. "Automated Testing of HVAC Systems for Commissioning." 1999. LBNL-43639.

Matson, N.E.; Feustel, H.E. "Residential Ventilation Systems." 1998. LBNL-40859.

Said, N.; Brown, W.; Walker, I. "Long Term Monitoring of an EIFS Clad Wall." Journal of Thermal Insulation and Building Envelopes, Volume 20, Pages 320-338. 1997.

Walker, I.; Modera, M.; Tuluca, A.; Graham, I. "Energy effectiveness of duct sealing and insulation in two multifamily buildings." Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 1, Pages 247-254, American Council for an Energy Efficient Economy, Washington, DC. 1996. LBL-38538 .

Abstract. Energy losses from forced air distribution systems have a significant impact on the energy efficiency of buildings. Little work has been done to quantify these losses in apartment buildings. In this paper we will discuss field measurements made on four forced air heating systems to evaluate the duct system energy losses to unconditioned basements. The apartments were heated by natural gas furnaces located in the basements. The systems had bare sheet metal ductwork exposed to the basement conditions. The pre- retrofit measurements were made on the systems after sealing large easily visible leaks. The post-retrofit measurements were made after wrapping the ducts in foil backed glass fiber insulation and additional leak sealing. Only the sections of duct exposed to the basement were retrofitted because only these sections were accessible. This study examines the potential energy savings for this type of limited retrofit. The energy losses were separated into leakage and conduction terms. Leakage measurements were made using register flowhood techniques. Conduction losses were estimated by measuring temperatures in the plenums and at the registers. Analysis of the measurements has shown typical reduction in leakage flow due to duct sealing of about 40%. The reduction in leakage translated into a reduction in energy consumption of about 10%.

Stetiu, C.; Feustel, H.E. "Phase Change Wallboard as an Alternative to Compressor Cooling in Residences?." Proceedings of the 1966 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 19, Pages 157-170, American Council for an Energy Efficient Economy, Washington, DC. 1996. LBL-38320.

Stetiu, C.; Feustel, H.E.; Nakano, Y. "Ventilation Control Strategies for Buildings with Hydronic Radiant Cooling in Hot Humid Climates." Proceedings of the RoomVent 1996, Yokohama, Japan, Pages 1, Institute of Industrial Science, University of Tokyo, Tokyo, Japan. 1996. LBNL-38320.

Sherman, M.H. "The Use of Blower-Door Data." Indoor Air, Volume 5, Pages 215-224. 1995. LBL-35173 .

Feustel, H. W. "Simplified Numerical Description of Latent Storage Characteristics for Phase Change Wallboard." 1995. LBL-36933.

3.2. Indoor Environmental Quality

Sherman, Max H.; Matson, Nance E. "Reducing Indoor Residential Exposures to Outdoor Pollutants." 2003. LBNL-51758 .

Abstract. Basic strategy for providing indoor air quality in residences is to dilute indoor sources with outdoor air. This strategy assumes that the outdoor air does not have pollutants at harmful levels or that the outdoor air is, at least, less polluted than the indoor air. When this is not the case, different strategies need to be employed to ensure adequate air quality in the indoor environment. These strategies include ventilation systems, filtration and other measures. These strategies can be used for several types of outdoor pollution, including smog, particulates and toxic air pollutants. This report reviews the impacts that typical outdoor air pollutants can have on the indoor environment and provides design and operational guidance for mitigating them. Poor quality air cannot be used for diluting indoor contaminants, but more generally it can become an indoor contaminant itself. This paper discusses strategies that use the building as protection against potentially hazardous outdoor pollutants, including widespread pollutants, accidental events, and potential attacks.

IED Staff. "A compilation of papers for the Indoor Air 2002 Conference in memory of Joan M. Daisey." 2002. LBNL-50419 .

Abstract. No Abstract available

Fisk, W.J.; Brager, G.; Burge, H.; Cummings, J.; Levin, H.; Loftness, V.; Mendell, M.J.; Persily, A.; Taylor, S.; Zhang, J.S. "Energy-related indoor environmental quality research: A priority agenda." 2002. LBNL-51328 .

Abstract. A multidisciplinary team of IEQ and energy researchers has defined a program of priority energy-related IEQ research. This paper describes the methods employed to develop the agenda, and 35 high priority research and development (R&D) project areas related to four broad goals: 1) identifying IEQ problems and opportunities; 2) developing and evaluating energy-efficient technologies for improving IEQ; 3) developing and evaluating energy-efficient practices for improving IEQ; and 4) encouraging or assisting the implementation of technologies or practices for improving IEQ. The identified R&D priorities reflect a strong need to benchmark IEQ conditions in small commercial buildings, schools, and residences. The R&D priorities also reflect the need to better understand how people are affected by IEQ conditions and by the related building characteristics and operation and maintenance practices. The associated research findings will provide a clearer definition of acceptable IEQ that is required to guide the development of technologies, practices, standards, and guidelines. Quantifying the effects of building characteristics and practices on IEQ conditions, in order to provide the basis for development of energy efficient and effective IEQ control measures, was also considered a priority. The development or advancement in a broad range of IEQ tools, technologies, and practices are also a major component of the priority research agenda. Consistent with the focus on "energy-related" research priorities, building ventilation and heating, ventilating and air conditioning (HVAC) systems and processes are very prominent in the agenda. Research related to moisture and microbiological problems, particularly within hot and humid climates, is also prominent within the agenda. The agenda tends to emphasize research on residences, small commercial buildings, and schools because these types of buildings have been underrepresented in prior research. Most of the research areas apply to both new construction and existing buildings. Nearly all of the recommended priority R&D project areas include tasks intended to facilitate the communication and implementation of the research results. In addition, the priority agenda includes several projects specifically designed to facilitate or stimulate the use of existing energy-efficient technologies and practices for improving IEQ. To assure that the research program continues to meet the needs of stakeholders and to facilitate the coordination of research among sponsors, the core team recommends an annual meeting attended by sponsors, a balanced group of stakeholders, and a selection of researchers implementing the agenda.

Fisk, W.J.; Brager, G.; Brook, M.; Burge, H.; Cole, J.; Cummings, J.; Levin, H.; Loftness, V.; Logee, T.; Mendell, M.J.; Persily, A.; Taylor, S.; Zhang, J. "A priority agenda for energy-related indoor environmental quality research." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 2, Pages 984-989, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-50612 .

Abstract. A multidisciplinary team of IEQ and energy researchers is working together to define a program of priority energy-related IEQ research. This paper describes the methods employed, ten high priority broad research and development (R&D) goals, and 34 high priority R&D project areas linked to these goals.

Tenwolde, A.; Walker, I.S. "Interior Moisture Design Loads for Residences." Proceedings of the ASHRAE/DOE/BTECC Thermal Performance of Exterior Envelopes of Whole Buildings VIII, Clearwater Beach, FL, ASHRAE, Atlanta, GA. 2001.

IED Staff. "Recent Research on Indoor Air Quality: A Compilation in Memory of Joan Daisey." 2000. LBNL-45463.

Morrison, G.C. "Ozone-Surface Interactions: Investigations of Mechanisms, Kinetics, Mass Transport, and Implications for Indoor Air Quality." 1999. LBNL-45044.

Ten Brinke, J.; Selvin, S.; Hodgson, A.T.; Fisk, W.J. "Development of new VOC exposure metrics and their relationship to sick building syndrome symptoms." Indoor Air, Volume 8, Pages 140-152. 1998. LBNL-42047.

Morrison, G.C.; Nazaroff, W.W.; Cano-Ruiz, A.; Hodgson, A.T.; Modera, M.P. "Indoor Air Quality Impacts of Ventilation Ducts: Ozone Removal and Emissions of Volatile Organic Compounds." Journal of Air and Waste Management Association, Volume 48, Pages 941-952. 1998. LBNL-43849.

Traynor, G.W.; Apte, M.G.; Chang, G. "Pollutant Emission Factors from Residential Natural Gas Appliances: A Literature Review." 1996. LBL-38123.

Hodgson, A.T. "Measurement of Indoor Air Quality in Two New Test Houses." 1996. LBNL-37929.

Daisey, J.; Lee, J. "Total exposure – Indoor and outdoor air in residential and occupational settings." Proceedings of the 2nd Colloquium on Particulate Air Pollution and Human Health, Park City, UT, Department of Community and Environmental Medicine, University of California, Irvine, CA. 1996.

Sherman, M.H. "The Use of Blower-Door Data." Indoor Air, Volume 5, Pages 215-224. 1995. LBL-35173 .

3.3. Infiltration, Ventilation and Air Cleaning

Walker, I.S. "Improving Air Handler Efficiency in Houses." Submitted to ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, August 22-27, 2004, American Council for an Energy Efficient Economy, Washington, DC. 2004. LBNL-54760 .

Abstract. Although furnaces, air conditioners and heat pumps have become significantly more efficient over the last couple of decades, residential air handlers have typical efficiencies of only 10% to 15% due to poor electric motor performance and aerodynamically poor fans and fan housings. Substantial increases in performance could be obtained through improved air handler design and construction. A prototype residential air handler intended to address these issues has recently been developed. The prototype and a standard production fan were tested in a full-scale duct system and test chamber at LBNL specifically designed for testing heating, ventilation, and air conditioning systems. The laboratory tests compared efficiency, total airflow, sensitivity to duct system flow resistance, and the effects of installation in a smaller cabinet. The test results showed that the prototype air handler had about twice the efficiency of the standard air handler (averaged over a wide range of operating conditions) and was less sensitive to duct system flow resistance changes. The performance of both air handlers was significantly reduced by reducing the clearance between the air handler and cabinet it was placed in. These test results showed that in addition to the large scope for performance improvement, air handler fans need to be tested in the cabinets they operate in.

Sherman, M.H. "ASHRAE's first residential ventilation standard." Submitted to Buildings IX Conference, Clearwater, FL, ASHRAE, Atlanta, GA. 2004. LBNL-54331.

Abstract. Abstract: ASHRAE has recently published its first residential ventilation standard, Standard 62.2-2003. This standard defines the roles of and minimum requirements for mechanical and natural ventilation systems and the building envelope intended to provide acceptable indoor air quality in low-rise residential buildings. The standard includes a minimum whole-house ventilation rate, local exhaust rates and other kinds of source control. This report summarizes the standard and indicates the key issues. Providing acceptable indoor air quality often depends more on source control than on ventilaton itself. Much source control depends on the interactions between ventilation and the building envelope. Unbalanced ventilation systems combined with a tight envelope can lead to building pressurization or depressurization. These building pressures can mitigate or enhance heat and mass transport through the building envelope, which can impact both energy use and moisture performance. These pressures can also impair systems and components not directly tied to ventilation, such as the operation of combustion appliances or entrainment of soil gas. Such "house-as-system" issues were important considerations in the development of the standard and will be discussed in the report. ASHRAE is continuing to develop and enhance these efforts by using a continuous maintenance process for the standard and by creation of a companion guideline to reflect the state of the art.

Sherman, M.H.; Hodgson, A.T. "Fomaldehyde as a Basis for Residential Ventilation Rates." Indoor Air, Volume 14, Pages 2-9. 2004. LBNL-49577 .

Abstract. Traditionally, houses in the U.S. have been ventilated by passive infiltration in combination with active window opening. However in recent years, the construction quality of residential building envelopes has been improved to reduce infiltration, and the use of windows for ventilation also may have decreased due to a number of factors. Thus, there has been increased interest in engineered ventilation systems for residences. The amount of ventilation provided by an engineered system should be set to protect occupants from unhealthy or objectionable exposures to indoor pollutants, while minimizing energy costs for conditioning incoming air. Determining the correct ventilation rate is a complex task, as there are numerous pollutants of potential concern, each having poorly characterized emission rates, and poorly defined acceptable levels of exposure. One ubiquitous pollutant in residences is formaldehyde. The sources of formaldehyde in new houses are reasonably understood, and there is a large body of literature on human health effects. This report examines the use of formaldehyde as a means of determining ventilation rates and uses existing data on emission rates of formaldehyde in new houses to derive recommended levels. Based on current, widely accepted concentration guidelines for formaldehyde, the minimum and guideline ventilation rates for most new houses are 0.28 and 0.5 air changes per hour, respectively.

Sherman, Max H. "ASHRAE's New Residential Ventilation Standard." ASHRAE Journal, Volume 46, Pages 149-156. 2004. LBNL-53776 .

Abstract. ASHRAE, the American Society of Heating, Refrigerating, and Air-conditioning Engineers, is the world leader in the field of heating, ventilating, air-conditioning and refrigeration (HVAC&R). ASHRAE has recently released a new residential ventilation standard reflecting minimum requirements for homes. They have also released a top ten list of things that homeowners should be aware of to protect their indoor environment. This article provides a summary of what homeowners and HVAC&R professionals should know regarding residential ventilation.

Walker, I.S.; Sherman, M.H. "Heat Recovery in Building Envelopes." 2003. LBNL 53484.

Abstract. Infiltration has traditionally been assumed to contribute to the energy load of a building by an amount equal to the product of the infiltration flow rate and the enthalpy difference between inside and outside. Some studies have indicated that application of such a simple formula may produce an unreasonably high contribution because of heat recovery within the building envelope. The major objective of this study was to provide an improved prediction of the energy load due to infiltration by introducing a correction factor that multiplies the expression for the conventional load. This paper discusses simplified analytical modeling and CFD simulations that examine infiltration heat recovery (IHR) in an attempt to quantify the magnitude of this effect for typical building envelopes. For comparison, we will also briefly examine the results of some full-scale field measurements IHR based on infiltration rates and energy use in real buildings. The results of this work showed that for houses with insulated walls the heat recovery is negligible due to the small fraction of the envelope that participates in heat exchange with the infiltrating air. However; there is the potential for IHR to have a significant effect for higher participation dynamic walls/ceilings or uninsulated walls. This result implies that the existing methods for evaluating infiltration related building loads provide adequate results for typical buildings.

Walker, Iain S.; Sherman, Max H. "Ventilation Technologies Scoping Study." 2003. LBNL-53811 .

Abstract. This document presents the findings of a scoping study commissioned by the Public Interest Energy Research (PIER) program of the California Energy Commission to determine what research is necessary to develop new residential ventilation requirements for California. This study is one of three companion efforts needed to complete the job of determining the needs of California, determining residential ventilation requirements, and determining appropriate ventilation technologies to meet these needs and requirements in an energy efficient manner. Rather than providing research results, this scoping study identifies important research questions along with the level of effort necessary to address these questions and the costs, risks, and benefits of pursuing alternative research questions. In approaching these questions and level of effort, feasibility and timing

were important considerations. The Commission has specified Summer 2005 as the latest date for completing this research in time to update the 2008 version of California's Energy Code (Title 24).

Sherman, Max H.; Chan, Wanyu R. "Building Airtightness: Research and Practice." State of the Art in Ventilation, Pages 8-12, James & James. 2003. LBNL-53356 .

Abstract. This report summarizes the state of the art on building air tightness by reviewing the current and recent literature on both research and practice. The focus of this report is on techniques to measure the tightness of the building envelope and on what has been learned by doing so. This report reviews over 100 of the most important publications relating to the topic. The report covered the fundamentals of air leakage including the hydrodynamics of leaks, which has led to all of the measurement techniques currently in use. The measurement techniques reviewed focus on the fan pressurization technique and its derivates, but the report covers novel techniques as well. Air tightness metrics allow data to be shared and compared and the basic air tightness metrics are reviewed and discussed as well as a brief discussion on norms and normalization. The bulk of the report discusses data which has been taken over the last twenty years and what it can tell us about buildings of different types, locations and properties.

McWilliams, Jennifer. "Review of air flow measurement techniques." 2003. LBNL-49747 .

Abstract. Airflow measurement techniques are necessary to determine the most basic of indoor air quality questions: "Is there enough fresh air to provide a healthy environment for the occupants of the building?" This paper outlines airflow measurement techniques, but it does not make recommendations for techniques that should be used. The airflows that will be discussed are those within a room or zone, those between rooms or zones, such as through doorways (open or closed) or passive vents, those between the building and outdoors, and those through mechanical air distribution systems. Techniques that are highlighted include particle streak velocimetry, hot wire anemometry, fan pressurization (measuring flow at a given pressure), tracer gas, acoustic methods for leak size determination, the Delta Q test to determine duct leakage flows, and flow hood measurements. Because tracer gas techniques are widely used to measure airflow, this topic is broken down into sections as follows: decay, pulse injection, constant injection, constant concentration, passive sampling, and single and multiple gas measurements for multiple zones. Selected papers are annotated, and a bibliography is included for each topic with full abstracts.

Chan, W.R.; Price, P. N.; Sohn, M.D.; Gadgil, A.J. "Analysis of U.S. Residential Air Leakage Database." 2003. LBNL-53367 .

Abstract. The air leakage of a building envelope can be determined from fan pressurization measurements with a blower door. More than 70,000 air leakage measurements have been compiled into a database. In addition to air leakage, the database includes other important characteristics of the dwellings tested, such as floor area, year built, and location. There are also data for some houses on the presence of heating ducts, and floor/basement construction type. The purpose of this work is to identify house characteristics that can be used to predict air leakage. We found that the distribution of leakage normalized with floor area of the house is roughly lognormal. Year built and floor area are the two most significant factors to consider when predicting air leakage: older and smaller houses tend to have higher normalized leakage areas compared to newer and larger ones. Results from multiple linear regression of normalized leakage with respect to these two factors are presented for three types of houses: low-income, energy-efficient, and conventional. We demonstrate a method of using the regression model in conjunction with housing characteristics published by the US Census Bureau to derive a distribution that describes the air leakage of the single-family detached housing stock. Comparison of our estimates with published datasets of air exchange rates suggests that the regression model generates accurate estimates of air leakage distribution.

Wray, Craig P. "Suite Ventilation Characteristics of Current Canadian Mid-and High-Rise Residential Buildings." ASHRAE Transactions, Volume 110 (Part 2). 2002. LBNL-43254 .

Abstract. This paper characterizes ventilation in residential suites located in ten buildings in major metropolitan areas of Canada. All buildings were between six and thirty-two stories tall and were

built between 1990 and 1995. 1. The key findings from field performance tests of these buildings were: 2. Corridor supply airflows usually did not meet design flows. 3. Makeup air paths for suite exhaust were not properly designed. 4. Suite access door leakage was highly variable and usually did not meet smoke control requirements. 5. Airflow from the corridor through the suite access door leakage appeared to be the primary ventilation air supply for suites. 6. Suites were usually well-ventilated, but some were marginally- or under-ventilated. 7. Poor pressure control often allowed transfer air from one suite to another. Inter-suite transfer air fractions ranged from 0 to 45%, with an average of 19%. In summary, this work showed suite ventilation can be highly influenced by corridor supply flows, by the treatment of corridor access doors, and by transfer airflows. As a result, suite ventilation at any given time in current mid- and high-rise residential buildings is very difficult to predict. To ensure suite ventilation performs as intended under all operating conditions, the building industry needs to address the identified problems through improved ventilation design, operation, and maintenance practices.

Theaker, I.G.; Wray, C.P. "Ventilation System Design of Recent Canadian Multi-Unit Residential Buildings." ASHRAE Transactions, Volume 106. 2002.

Abstract. No Abstract available.

Sherman, M.H.; Matson, N.E. "Air Tightness of New U.S. Houses: A Preliminary Report." 2002. LBNL-48671 .

Abstract. Most dwellings in the United States are ventilated primarily through leaks in the building shell (i.e., infiltration) rather than by whole-house mechanical ventilation systems. Consequently, quantification of envelope air-tightness is critical to determining how much energy is being lost through infiltration and how much infiltration is contributing toward ventilation requirements. Envelope air tightness and air leakage can be determined from fan pressurization measurements with a blower door. Tens of thousands of unique fan pressurization measurements have been made of U.S. dwellings over the past decades. LBNL has collected the available data on residential infiltration into its Residential Diagnostics Database, with support from the U.S. Department of Energy. This report documents the envelope air leakage section of the LBNL database, with particular emphasis on new construction. The work reported here is an update of similar efforts carried out a decade ago, which used available data largely focused on the housing stock, rather than on new construction. The current effort emphasizes shell tightness measurements made on houses soon after they are built. These newer data come from over two dozen datasets, including over 73,000 measurements spread throughout a majority of the U.S. Roughly one-third of the measurements are for houses identified as energy-efficient through participation in a government or utility program. As a result, the characteristics reported here provide a quantitative estimate of the impact that energy-efficiency programs have on envelope tightness in the US, as well as on trends in construction.

Abadie, M.O.; Finlayson, E.O.; Gadgil, A. J. "Infiltration heat recovery in building walls: Computational fluid dynamics investigations results." 2002. LBNL-51324 .

Abstract. Conventional calculations of heating (and cooling) loads for buildings assume that conduction heat loss (or gain) through walls is independent of air infiltration heat loss (or gain). During passage through the building envelope, infiltrating air substantially exchanges heat wall insulation leading to partial recovery of heat conducted through the wall. The Infiltration Heat Recovery (IHR) factor was introduced to quantify the heat recovery and correct the conventional calculations. In this study, Computational Fluid Dynamics was to calculate infiltration heat recovery under a range of idealized conditions, specifically to understand factors that influence it, and assess its significance in building heat load calculations. This study shows for the first time the important effect of the external boundary layers on conduction and infiltration heat loads. Results show (under the idealized conditions studied here) that (1) the interior details of the wall encountered in the leakage path (i.e., insulated or empty walls) do not greatly influence the IHR, the overall relative location of the cracks (i.e., inlet and outlet locations on the wall) has the largest influence on the IHR magnitude, (2) external boundary layers on the walls substantially contribute to IHR and (3) the relative error in

heat load calculations resulting from the use of the conventional calculational method (i.e., ignoring IHR) is between 3% and 13% for infiltrating flows typically found in residential buildings.

Sherman, M.H.; Walker, I.S. "Heat Recovery in Building Envelopes." Proceedings of the ASHRAE/DOE/BTECC Thermal Performance of Exterior Envelopes of Buildings VIII, Clearwater Beach, FL, ASHRAE, Atlanta, GA. 2001. LBNL-47329 .

Wray, C.P.; Matson, N.E.; Sherman, M.H. "Selecting Whole-House Ventilation Strategies to Meet Proposed ASHRAE 62.2: Energy Cost Considerations." ASHRAE Transactions, Volume 106, Pages 681-691. 2000. LBNL-44479 .

Abstract. ASHRAE Standard 62.2P is being proposed to address residential ventilation issues. As housing, especially new housing, gets more airtight and better insulated, it has become clear that many homes are under-ventilated. The Standard contains requirements that provide minimum ventilation rates and source control measures necessary for acceptable indoor air quality. This paper uses previously reported analytical techniques to compare the energy costs of various ventilation strategies for a wide variety of climates and housing types. For new construction, we conclude that mechanical ventilation is needed. In new houses with gas heating, the cheapest whole-house system is a central exhaust fan. The marginal energy costs to provide such ventilation are on the order of 50cents per day. However, other systems can be more appropriate when depressurization, filtration, moisture, and more expensive heating fuels are considered. For most of the existing housing stock, we conclude that infiltration provides adequate ventilation.

Buchanan, C.R.; Sherman, M.H. "A Mathematical Model for Infiltration Heat Recovery." 2000. LBNL-44294 .

Walker, I.S. "Distribution System Leakage Impacts on Apartment Building Ventilation Rates." ASHRAE Transactions, Volume 105, Pages 943-950. 1999. LBNL- 42127.

Abstract. Forced air distribution systems in residential buildings are often located outside conditioned space, for example in attics, crawlspaces, garages and basements. Leaks from the ducts to these unconditioned spaces or outside can change flows through the registers and change the ventilation rates of the conditioned spaces. In this study, duct leakage flows were measured in several low-rise apartment buildings. The leakage flow measurements and other data about the apartments were used to develop a prototype apartment building. The multizone airflow model COMIS was then used on this prototype building to determine internal flows within the building, air flows through the building envelope and the impacts of the duct leakage on the ventilation rates. The effects of sealing the duct leaks were also examined in order to determine changes in infiltration rates resulting from duct retrofits. The simulation results showed that for the prototype tested here, the excess return leakage tended to decrease envelope infiltration flows by about 20% but the total infiltration load including return duct leaks more than doubled during system operation.

Sherman, M. "ASHRAE's Residential Ventilation Standard: Exigesis of Proposed Standard 62.2." ASHRAE Journal. 1999. LBNL-42975 .

Diamond, R.C.; Feustel, H.E.; Matson, N. "A Guide to Energy Efficient Ventilation in Apartment Buildings, US Department of Energy (DOE/EE-0196)." 1999. LBNL-43641.

Wray, C.P.; Theaker, I.G.; Moffatt, P. "Field Testing to Characterize Suite Ventilation in Recently Constructed Mid- and High-Rise Residential Buildings." 1998.

Walker, I.S.; Wilson, D.J. "Field Validation of Algebraic Equations for Stack and Wind Driven Air Infiltration Calculations." HVAC&R Research, Volume 4, Pages 119-139. 1998. LBNL-42361 .

Abstract. Explicit algebraic equations for calculation of wind and stack driven ventilation were developed by parametrically matching exact solutions to the flow equations for building envelopes. These separate wind and stack effect flow calculation procedures were incorporated in a simple natural ventilation model, AIM- 2, with empirical functions for superposition of wind and stack effect and for estimating wind shelter. The major improvements over previous simplified ventilation

calculations are: a power law pressure-flow relationship is used to develop the flow equations form first principles, the furnace or fireplace flue is included as a separate leakage site and the model differentiates between houses with basements (or slab-on- grade) and crawlspaces. Over 3400 hours of measured ventilation rates from the test houses at the Alberta Home Heating Research Facility were used to validate the predictions of ventilation rates and to compare the AIM-2 predictions to those of other ventilation models. The AIM-2 model had bias and scatter errors of less than 15% for wind-dominated ventilation, and less than 7% for buoyancy ("stack-effect") dominated cases.

Walker, I.S.; Wilson, D.J.; Sherman, M.H. "A Comparison of the Power Law to Quadratic Formulations for Air Infiltration Calculations." Energy and Buildings, Volume 27, Pages 293-299. 1998. LBNL-41447 .

Abstract. Although the power law has been broadly accepted in measurement and air infiltration standards, and in many air infiltration calculation methods, the assumption that the power law is true over the range of pressures that a building envelope experiences has not been well documented. In this paper, we examine the validity of the power law through theoretical analysis, laboratory measurements of crack flow and detailed field tests of building envelopes. The results of the theoretical considerations, and field and laboratory measurements indicate that the power law is valid for low pressure building envelope leakage.

Sherman, M.H; Dickerhoff, D.J. "Air Tightness of U.S. Dwellings." ASHRAE Transactions, Volume 104, Pages 1359-1367. 1998.

Feustel, H.E; Diamond, R.C. "Ventilation in Highrise Apartments." Proceedings of the Room Vent 1998 Conference, Stockholm, Sweden, KTH, Stockholm, Sweden. 1998. LBNL-43642.

Buchanan, C.R.; Sherman, M.H. "CFD Simulation of Infiltration Heat Recovery." Proceedings of the 19th AIVC Conference, Oslo, Norway, Air Infiltration and Ventilation Centre, Coventry, United Kingdom. 1998. LBNL-42098.

Apte, M.G.; Nero, A.V.; Revzan, K.L. "LBL Meteorological Database for the United States." 1998. LBL-33854.

Forowicz, T. "New Generation of Sofware: Modeling of Energy Demands for Residential Ventilation with HTML Interface." 1997. LBNL-40423.

Walker, I.S.; Wilson, D.J.; Forest, T.W. "A Wind Shadow Model for Air Infiltration Sheltering by Upwind Obstacles." ASHRAE HVAC&R Research Journal, Volume 2, Pages 265-283. 1996.

Abstract. The wind shadow model has been developed to calculate the wind sheltering effects of upwind obstacles for air infiltration calculations. This effect must be determined for infiltration calculations because, in almost all situations, only the unobstructed mean wind speed is known for a building site. This model has adapted the theoretical calculation procedures developed for far wake centreline velocity deficit calculations to near field flows, where shelter has a significant effect. The model uses the concept of a wind shadow projected downstream by upwind buildings to determine the effect of wake velocity reduction on building surfaces. The turbulent nature of the wake is accounted for by "flapping" the wake over a range of wind directions. The effectiveness of this model in accounting for sheltering effects in infiltration calculations has been examined by comparing infiltration model predictions including the wind shadow model to measured data from a row of test houses. The measured data covered a wide range of wind speeds, wind directions and leakage distributions by using over five thousand hours of infiltration measurements from five houses.

Sherman, M.; Matson, N. "Residential Ventilation and Energy Characteristics." 1996. LBNL-39036 .

Feustel, H.E.; Diamond, R.C. "Diagnostics and measurements of infiltration and ventilation systems in high-rise apartment buildings." Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 1, Pages 95-101, American Council for an Energy Efficient Economy, Washington, DC. 1996. LBL-38103.

Diamond, R.C.; Feustel, H.E.; Dickerhoff, D.J. "Ventilation and Infiltration in Highrise Apartment Buildings." 1996. LBNL-38103.

Walker, I.S.; Forest, T.W. "Field Measurements of Ventilation Rates in Attics." Building and Environment, Volume 30, Pages 333-347. 1995.

Abstract. Field tests were carried out in two flat ceiling, residential attics at a dedicated test site over a two year period. The scope of this paper is to present measurements of ventilation rates, indoor-attic exchange rates, temperatures and wood moisture contents at various locations in the attics. Attic ventilation rates are correlated with wind speed, wind direction, and attic-outdoor temperature difference. Wind speed is shown to be the dominant driving force for ventilation; however, wind direction is important particularly when the attic is sheltered.

Walker, I.S.; Forest, T.W.; Wilson, D.J. "A Simple Calculation Method for Attic Ventilation Rates." Proceedings of the 16th AIVC Conference, Volume 1, Pages 221-232, Air Infiltration and Ventilation Centre, Coventry, Great Britain. 1995. LBL-36879.

Abstract. The ventilation of an attic is critical in estimating heating and cooling loads for buildings because the air temperature in the attic is highly sensitive to ventilation rate. In addition, attic ventilation is an important parameter for determining moisture accumulation in attic spaces that can lead to structural damage and reduced insulation effectiveness. Historically, attic venting has been a common method for controlling attic temperature and moisture, but there have been no calculation techniques available to determine attic ventilation rates. Current practice is to use rules of thumb for estimating attic vent areas. Simple algebraic relationships are developed here, using functions fitted to an exact numerical solution for air flow through attic envelopes. This algebraic model (AVENT) was developed to be easy to use as diagnostic or design tool. Key factors included in the model are: climate (wind and stack effect), wind shelter, leakage distribution and total attic leakage. This paper validates the model predictions by comparing to measured data from two attics at the Alberta Home Heating Research Facility (AHHRF). Average errors for the model are about 15% compared to the measured ventilation rates.

3.4. Radon

Prill, R.; Fisk, W.J. "Long Term Performance of Radon mitigation systems." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 2, Pages 641-646, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-50041 .

Abstract. Researchers installed radon mitigation systems in 12 houses in Spokane, Washington and Coeur d'Alene, Idaho during the heating season 1985 – 1986 and continued to monitor indoor radon quarterly and annually for ten years. The mitigation systems included active sub-slab ventilation, basement over-pressurization, and crawlspace isolation and ventilation. The occupants reported various operational problems with these early mitigation systems. The long-term radon measurements were essential to track the effectiveness of the mitigation systems over time. All 12 homes were visited during the second year of the study, while a second set 5 homes was visited during the fifth year to determine the cause(s) of increased radon in the homes. During these visits, the mitigation systems were inspected and measurements of system performance were made. Maintenance and modifications were performed to improve system performance in these homes.

Hopke, P.K.; Borak, T.B.; Doull, J.; Cleaver, J.E.; Eckerman, K.F.; Gundersen, L.C.; Harley, N.H.; Hess, C.E.; Kinner, N.E.; Kopecky, K.J.; McKone, T.E.; Sextro, R.G.; Simon, L.G. "Health risks due to radon in drinking water." Environmental Science & Technology, Volume 34, Pages 921-926. 2000.

Riley, W.J.; Robinson, A.L.; Gadgil, A.; Nazaroff, W. "Effects of variable wind speed and direction on radon transport from soil into buildings: model development and exploratory results." Atmospheric Environment, Volume 33, Pages 2157-2168. 1999. LBNL-43652 .

Abstract. We describe a novel modeling technique, based on Duhamel's theorem, to study the effects of time-varying winds on radon transport in soil near buildings. The technique, implemented in the model RapidSTART, reduces computational times for transient, three-dimensional, wind-induced soil-gas and radon transport by three to four orders of magnitude compared with conventional finite-dierence models. To test model performance, we compared its predictions to analytical solutions of

one-dimensional soil-column flow, finite-difference simulations of flow around a full-scale house, and measurements of transient soil-gas and radon entry into an experimental basement structure. These comparisons demonstrate that RapidSTART accurately simulates time-dependent radon transport through soil and its entry into buildings. As demonstrated in a previous study, steady winds can significantly affect radon entry. In this paper, we extend the findings of that study by applying RapidSTART to explore the impacts of fluctuating wind speed and direction on radon entry into a prototypical house. In soils with moderate to high permeability, wind fluctuations have a small to moderate effect on the soil-gas radon concentration field and entry rate into the building. Fluctuating wind direction dominates the impact on radon entry rates, while fluctuating wind speed has little effect. For example, in a soil with a permeability of 10 10m2, diurnal oscillations in wind direction can increase the predicted radon entry rate by up to 30% compared to steady-state predictions. (1999 Elsevier Science Ltd. All rights reserved.

Garbesi, K.; A.L. Robinson; R.G. Sextro; W.W. Nazaroff. "Radon entry into houses: The importance of scale-dependent permeability." Health Physics, Volume 77, Pages 83-191. 1999. LBNL-44040.

Apte, M.G.; Price, P.N.; Nero, A.V.; Revzan, K.L. "Predicting Indoor Radon Concentrations in New Hampshire from Geologic Information and Other Covariates." Environmental Geology, Volume 37, Pages 181-194. 1999. LBNL-38961.

Ruzer, L.S.; Sextro, R.G. "Measurement of Radon Decay Products in Air by Alpha- and Beta-Spectrometry." Radiation Protection Dosimetry, Volume 72, Pages 43-48. 1997.

Robinson, A.L.; Sextro, R.G.; Riley, W.J. "Soil-Gas Entry Into Houses Driven By Atmospheric Pressure Fluctuations – the Influence of Soil Properties." Atmospheric Environment, Volume 31, Pages 1487-1495. 1997.

Robinson, A.L.; Sextro, R.G. "Radon Entry into Buildings Driven by Atmospheric Pressure Fluctuations." Environmental Science & Technology, Volume 31, Pages 1742-1748. 1997.

Price, P.N. "Predictions and Maps of County Mean Indoor Radon Concentrations in the Mid-Atlantic States." Health Physics, Volume 72, Pages 893-906. 1997.

Robinson, A.L.; Sextro, R.G.; Fisk, W.J. "Soil gas entry into an experimental basement driven by atmospheric pressure fluctuations, measurements, spectral analysis, and model comparison." Atmospheric Environment, Volume 31, Pages 1477-1485. 1996.

Riley, W.J.; Gadgil, A.J.; Bonnefous, Y.C.; Nazaroff, W.W. "The Effect of Steady Winds on Radon Entry into Houses." Atmospheric Environment, Volume 30, Pages 1167-1176. 1996. LBL-36372.

Riley, W.J.; Fisk, W.J.; Gadgil, A.J. "Regional and National Estimates of the Potential Energy Use, Energy Cost, and CO2 Emissions Associated with Radon Mitigation by Sub-Slab Depressurization." Energy and Buildings, Volume 24, Pages 203-212. 1996. LBL-36368.

Price, P.N.; Nero, A.V. "Joint Analysis of Long- and Short-Term Radon Monitoring Data from the Northern U.S." Environmental International, Volume 22, Pages 669-714. 1996. LBL-37276.

Garbesi, K.; Sextro, R.G.; Robinson, A.L.; Wooley, J.D.; Owens, J.A.; Nazaroff, W.W. "Scale Dependence of Soil Permeability to Air: Measurement Method and Field Investigation." Water Resource Research, Volume 32, Pages 547-560. 1996. LBL-35369.

Robinson, A.L.; Sextro, R.G. "Direct measurements of soil-gas entry into an experimental basement driven by atmospheric pressure fluctuations." Geophysical Research Letters, Volume 22, Pages 1929-1932. 1995. LBL-36743.

Robinson, A.L.; Sextro, RG. "The Influence of a Subslab Gravel Layer and Open Area on Soil-Gas and Radon Entry into Two Experimental Basements." Health Physics, Volume 69, Pages 367-377. 1995. LBL-35943.

Riley, W.J.; Gadgil, A.J.; Nazaroff, W.W. "Wind-induced Ground Pressures Around a Single-family House." Journal of Wind Engineering and Industrial Aerodynamics, Volume 61, Pages 153-167. 1995. LBL-38435.

Revzan, K. L.; Price, P. N.; Nero, A. V. "Bayesian Analysis of the Relationship Between Indoor Radon Concentrations and Predicitive Variables in US Houses." 1995. LBL-38194.

Price, P. N.; Nero, A. V.; Gelman, A. "Bayesian Prediction of Mean Indoor Radon Concentrations for Minnesota Counties." 1995. LBL-35818.

Price, P.N. "The Regression Effect as a Cause of the Nonlinear Relationship Between Short- and Long-Term Radon Concentration Measurements." Health Physics Society, Volume 69, Pages 111-114. 1995. LBL-35819.

Fisk, W.J.; Prill, R.J.; Fisk, J.W.; Bonnefous, Y.C.; Gadgil, A.J.; Riley, W.J. "New Methods of Energy Efficient Radon Mitigation." Health Physics, Volume 68, Pages 689-698. 1995. LBL-36519.

3.5. Thermal Distribtion (Ducts)

Sherman, M.; Walker, I.S. "Duct Tape Durability Testing." 2004. LBNL-54767 .

Abstract. Duct leakage has been identified as a major source of energy loss in residential buildings. Most duct leakage occurs at the connections to registers, plenums or branches in the duct system. At each of these connections a method of sealing the duct system is required. Typical sealing methods include tapes or mastics applied around the joints in the system. Field examinations of duct systems have typically shown that these seals tend to fail over extended periods of time. The Lawrence Berkeley National Laboratory has been testing sealant durability for several years. Typical duct tape (i.e. fabric backed tapes with natural rubber adhesives) was found to fail more rapidly than all other duct sealants. This report summarizes the results of duct sealant durability testing of four UL 181B-FX listed duct tapes (two cloth tapes, a foil tape and an Oriented Polypropylene (OPP) tape). One of the cloth tapes was specifically developed in collaboration with a tape manufacturer to perform better in our durability testing. The tests involved the aging of common core-to-collar joints of flexible duct to sheet metal collars, and sheet metal collar-to-plenum joints. Periodic air leakage tests and visual inspection were used to document changes in sealant performance. The current study is a continuation of ongoing research at Lawrence Berkeley National Laboratory (Sherman and Walker, 2003; Walker and Sherman 2003; Walker and Sherman 2000; Sherman and Walker, 1998) that has the following objectives and outcomes:

Walker, I.S.; Wray, C.P. "Evaluation of Flow Capture Techniques for Measuring HVAC Grille Airflows." ASHRAE Transactions, Volume 109. 2003. LBNL-51550 .

Abstract. This paper discusses the accuracy of commercially available flow hoods for residential applications. Results of laboratory and field tests indicate these hoods can be inadequate to measure airflows in residential systems, and there can be large measurement discrepancies between different flow hoods. The errors are due to poor calibrations, sensitivity of the hoods to grille airflow non-uniformities, and flow changes from added flow resistance. It is possible to obtain reasonable results using some flow hoods if the field tests are carefully done, the grilles are appropriate, and grille location does not restrict flow hood placement. We also evaluated several simple flow capture techniques for measuring grille airflows that could be adopted by the HVAC industry and homeowners as simple diagnostics. These simple techniques can be as accurate as commercially available devices. Our test results also show that current calibration procedures for flow hoods do not account for field application problems. As a result, agencies such as ASHRAE or ASTM need to develop a new standard for flow hood calibration, along with a new measurement standard to address field use of flow capture techniques.

Walker, Iain S.; Wray, Craig P.; Guillot, Cryil; Masson, S. "Evaluation of Commercially AvailableTechniques and Development of Simplified Methods for Measuring Grille Airflows in HVAC Systems." 2003. LBNL-51551 .

Abstract. This report discusses the accuracy of flow hoods for residential applications, based on laboratory tests and field studies. The results indicate that commercially available hoods are often inadequate to measure flows in residential systems, and that there can be a wide range of performance between different flow hoods. The errors are due to poor calibrations, sensitivity of existing hoods to

grille flow non-uniformities, and flow changes from added flow resistance. We also evaluated several simple techniques for measuring register airflows that could be adopted by the HVAC industry and homeowners as simple diagnostics that are often as accurate as commercially available devices. Our test results also show that current calibration procedures for flow hoods do not account for field application problems. As a result, organizations such as ASHRAE or ASTM need to develop a new standard for flow hood calibration, along with a new measurement standard to address field use of flow hoods.

Walker, Iain S.; Brenner, Douglas E.; Sherman, Max H.; Dickerhoff, Darryl J. "Evaluation of PEGIT Duct Connection System." 2003. LBNL-43382 .

Abstract. Most air duct system components are assembled in the field and are mechanically fastened by sheet metal screws (for sheet metal-to-sheet metal) or by drawbands (for flex duct-to-sheet metal). Air sealing is separate from this mechanical fastening and is usually achieved using tape or mastic products after mechanical fastening. Field observations have shown that mechanical fastening rarely meets code or manufacturers requirements and that sealing procedures are similarly inconsistent. To address these problems, Proctor Engineering Group (PEG) is developing a system of joining ducts (called PEGIT) that combines the mechanical fastening and sealing into a single self-contained procedure. The PEGIT system uses a shaped flexible seal between specially designed sheet metal duct fittings to both seal and fasten duct sections together. Figure 1 shows the inner duct fitting complete with rubber seal. This seal provides the air seal for the completed fitting and is shaped to allow the inner and outer fittings to slide together, and then to lock the fittings in place. The illustration in Figure 2 shows the approximate cross section of the rubber seal that shows how the seal has a lip that is angled backwards. This angled lip allows the joint to be pushed together by folding flat but then its long axis makes it stiff in the pulling apart direction. This study was undertaken to assist PEG in some of the design aspects of this system and to test the performance of the PEGIT system.

Walker, Iain S.; Guillot, Cyril. "Experimental Evaluation of Gas Filled Plenum Duct Insulation." 2003. LBNL-52084 .

Abstract. Forced-air heating and cooling system ducts are often located outside conditioned space in US houses. For these systems to perform efficiently it is important that these ducts be well insulated. Common practice is to use a glass fiber wrap around the ducts – either field applied or more commonly, integrated into a flexible duct. Most duct insulation has an R-value of 4.2, with R6 and R8 ducts also occasionally used. With glass fiber insulation being about R4 per inch (RSI 0.28/cm), this adds 2 to 4 inches (50 to 100 mm) to the duct diameter. Some building codes are now requiring these higher insulation levels, for example, the EPA requires the use of R6 ducts (for Energy Star ducts: http://www.epa.gov/hhiptool/PDF/Duct_Spec_2002.PDF), and International Energy Conservation Code (BOCA 2003) requires R8 ducts. The difficulty with adding insulation to ducts is the increase in diameter of the ducts that makes them expensive to transport because they take up a large volume and are difficult to install in the confined spaces available for ducts in houses. The objective of this study was to evaluate Gas Filled Plenum (GFP) technology as an alternative duct insulation. GFP ducts have the potential to provide greater insulation levels than existing ducts (for a given thickness of insulation or size of duct) and provide cost savings in transportation. These transportation cost savings are based on the idea of shipping the GFP ducts empty and inflating them on-site. To evaluate this technology for ducts we constructed a prototype duct and determined both its flow and heat transfer resistance in LBNL's duct testing laboratories. The GFP technology works by encapsulating a gas (usually air – but other noble gases such as Argon or Krypton can provide significant increases in thermal resistance with increased cost) in a metalized film jacket. A honeycomb structure is used to keep individual gas pockets small to minimize convection heat transfer. A metallic finish (usually aluminum) minimizes radiation heat transfer between the surfaces.

Walker, I.S.; Mingee, M.D.; Brenner, D.E. "Improving Air Handler Efficiency in Residential HVAC Applications." 2003. LBNL-53606 .

Abstract. In continuing the development of energy efficiency standards, consideration has turned to air handlers used for heating and air conditioning of consumer residences. These air handlers have typical efficiencies of about 10% to 15% due to poor electric motor performance and aerodynamically poor fans and fan housings. This study was undertaken to examine some of these performance issues, under carefully controlled laboratory conditions, to support potential regulatory changes. In addition, this study examined the performance of a prototype air handler fan assembly that offers the potential for substantial increases in performance. This prototype and a standard production fan were tested in a full-scale duct system and test chamber at LBNL which was specifically designed for testing heating, ventilation, and air conditioning systems. The laboratory tests compared efficiency, total airflow, sensitivity to duct system flow resistance, and the effects of installation in a smaller cabinet. The test results showed that, averaged over a wide range of operating conditions, the prototype air handler had about twice the efficiency of the standard air handler and was less sensitive to duct system flow resistance changes. The performance of both air handlers was significantly reduced by reducing the space between the air handler and the cabinet it was installed in. Therefore any fan rating needs to be performed using the actual cabinet it will be used

Siegel, J.; Walker, I.S. "Integrating ducts into the conditioned space: Successes and challenges." Architectural Engineering Institute Conference, Austin, TX. 2003. LBNL-55675 .

Abstract. In residential and light commercial construction in the United States, heating and cooling ducts are often located outside the thermal or pressure boundary of the conditioned space. This location is selected for aesthetic and space requirement reasons. Typical duct locations include attics, above dropped ceilings, crawlspaces, and attached garages. A wide body of literature has found that distribution system conduction and air leakage can cause 30-40% energy losses before cooling and heating air reaches the conditioned space. Recent innovative attempts at locating ducts in the conditioned space have had mixed results in terms of improving duct efficiency. Some of these strategies include cathedralizing attics (sealing and insulating at the attic roofline) and locating ducts in interstitial spaces. This paper reviews modeling studies that suggest substantial savings could be realized from these strategies and presents field measurements which reveal that construction planning and execution errors can prevent these strategies from being widely applied or from being effective when they are applied. These types of problems will need to be overcome for effective integration of ducts into the conditioned space.

Sherman, M.H.; Walker, I.S. "Advanced Duct Sealant Testing." 2003. LBNL-53547 .

Abstract. Duct leakage is a major source of energy loss in residential buildings. Most duct leakage occurs at the connections to registers, plenums, or branches in the duct system. At each of these connections, a method of sealing the duct system is required. Typical sealing methods include tapes or mastics applied around the joints in the system. Field examinations of duct systems have shown that taped seals tend to fail over extended periods of time. The Lawrence Berkeley National Laboratory (LBNL) has been testing sealant durability for several years. Accelerated test methods were used that continuously expose duct sealants to elevated temperatures (200 to 212°F (93 to 100°C)). We found that typical duct tape (i.e., fabric backed tapes with natural rubber adhesives) fails more rapidly than all other duct sealants. We also tested advanced tape products being developed by major manufacturers. The results of these tests showed that the major weaknesses of the tapes that fail are the use of natural rubber adhesives and the mechanical properties of the backing. The test results also showed that the current UL listings are inadequate for indicating durability and many tapes showed significant failure when testing using UL 181 B-FX procedures. In addition, the clamps required (but not evaluated) by UL-181B-FX had many failures and their durability also required evaluation. An accelerated test method developed by LBNL is being used as a basis for an ASTM standard under sub-committee E6.41.

Walker, I.S.; Dickerhoff, D.J.; Sherman, M.H. "The Delta Q method of testing the air leakage of ducts." Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 1, Pages 327-338, American Council for an Energy Efficient Economy, Washington, DC. 2002. LBNL-49749 .

Abstract. The DeltaQ test has been developed in order to provide better estimates of forced

air system air leakage for use in energy efficiency calculations and for compliance testing of duct systems. The DeltaQ test combines a model of the house and duct system with the results of house pressurization tests with the air handler on and off to determine the duct leakage air flows to outside conditioned space at operating conditions. The key advantage of the DeltaQ test over other methods is that it determines the air leakage flows directly, rather than requiring interpretation of indirect measurements. The results from over 200 field and laboratory tests are presented. The laboratory tests have shown that the DeltaQ repeatability uncertainties are typically 1% or less of system fan flow and that the accuracy of the test is between 1.3% and 2.5% of fan flow (or 13 cfm to 25 cfm (6 to 12 l/s) for this system).

Siegel, J.A.; Nazaroff, W.W. "Modeling Particle Deposition on HVAC Heat Exchangers." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 521-526, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49339 .

Abstract. Fouling of fin-and-tube heat exchangers by particle deposition leads to diminished effectiveness in supplying ventilation and air conditioning. This paper explores mechanisms that cause particle deposition on heat exchanger surfaces. We present a model that accounts for impaction, diffusion, gravitational settling, and turbulence. Simulation results suggest that some submicron particles deposit in the heat exchanger core, but do not cause significant performance impacts. Particles between 1 and 10 μm deposit with probabilities ranging from $1 - 20$ % with fin edge impaction representing the dominant mechanism. Particles larger than 10 μm deposit by impaction on refrigerant tubes, gravitational settling on fin corrugations, and mechanisms associated with turbulent airflow. The model results agree reasonably well with experimental data, but the deposition of larger particles at high velocities is underpredicted. Geometric factors, such as discontinuities in the fins, are hypothesized to be responsible for the discrepancy.

Siegel, J.A.; McWilliams, J.A.; Walker, I.S. "Comparison between predicted duct effectiveness from proposed ASHRAE standard 152P and measured field data for residential forced air cooling systems." ASHRAE Transactions, Volume 109. 2002. LBNL-50008 .

Abstract. The proposed ASHRAE Standard 152P "Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems" (ASHRAE 2002) has recently completed its second public review. As part of the standard development process, this study compares the forced air distribution system ratings provided by the public review draft of Standard 152P to measured field results. 58 field tests were performed on cooling systems in 11 homes in the summers of 1998 and 1999. Seven of these houses had standard attics with insulation on the attic floor and a well-vented attic space. The other four houses had unvented attics where the insulation is placed directly under the roof deck and the attic space is not deliberately vented. Each house was tested under a range of summer weather conditions at each particular site, and in some cases the amount of duct leakage was intentionally varied. The comparison between 152P predicted efficiencies and the measured results includes evaluation of the effects of weather, duct location, thermal conditions, duct leakage, and system capacity. The results showed that the difference between measured delivery effectiveness and that calculated using proposed Standard 152P is about 5 percentage points if weather data, duct leakage and air handler flow are well known. However, the accuracy of the standard is strongly dependent on having good measurements of duct leakage and system airflow. Given that the uncertainty in the measured delivery effectiveness is typically also about 5 percentage points, the Standard 152P results are acceptably close to the measured data.

Abushakra, B.; Walker, I.S.; Sherman, M.H. "A study of pressure losses in residential air distribution systems." Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 1, Pages 1-14, American Council for an Energy Efficient Economy. 2002. LBNL-49700 .

Abstract. An experimental study was conducted to evaluate the pressure drop characteristics of residential duct system components that are either not available or not thoroughly (sometimes incorrectly) described in existing duct design literature. The tests were designed to imitate cases normally found in typical residential and light commercial installations. The study included three different sizes of flexible ducts, under different compression configurations, splitter boxes, supply

boots, and a fresh air intake hood. The experimental tests conformed to ASHRAE Standard 120P – Methods of Testing to Determine Flow Resistance of HVAC Air Ducts and Fittings. The flexible duct study covered compressibility and bending effects on the total pressure drop, and the results showed that the available published references tend to underestimate the effects of compression in flexible ducts that can increase pressure drops by up to a factor of nine. The supply boots were tested under different configurations including a setup where a flexible duct elbow connection was considered as an integral part of the supply boot. The supply boots results showed that diffusers can increase the pressure drop by up to a factor of two in exit fittings, and the installation configuration can increase the pressure drop by up to a factor of five. The results showed that it is crucial for designers and contractors to be aware of the compressibility effects of the flexible duct, and the installation of supply boots and diffusers.

Abushakra, B. "Longevity of duct tape in residential air distribution systems: 1-D, 2-D, and 3-D joints." 2002. LBNL-51099 .

Abstract. No Abstract available

Walker, I.S.; Siegel, J.A.; Degenetais, G. "Simulation of Residential HVAC System Performance." Proceedings of the ESIM 2001 Conference, Ontario, Canada, Pages 43-50, CANMET Energy Technology Centre/Natural Resources Canada, Ottawa, Canada. 2001. LBNL-47622 .

Abstract. In many parts of North America residential HVAC systems are installed outside conditioned space. This leads to significant energy losses and poor occupant comfort due to conduction and air leakage losses from the air distribution ducts. In addition, cooling equipment performance is sensitive to air flow and refrigerant charge that have been found to be far from manufacturers specifications in most systems. The simulation techniques discussed in this paper were developed in an effort to provide guidance on the savings potentials and comfort gains that can be achieved by improving ducts (sealing air leaks) and equipment (correct air-flow and refrigerant charge). The simulations include the complex air flow and thermal interactions between duct systems, their surroundings and the conditioned space. They also include cooling equipment response to air flow and refrigerant charge effects. Another key aspect of the simulations is that they are dynamic – which accounts for cyclic losses from the HVAC system and the effect of cycle length on energy and comfort performance.

Walker, I.S. "Sensitivity of forced air distribution system efficiency to climate, duct location, air leakage and insulation." 2001. LBNL-43371 .

Abstract. This study was performed in order to find suitable efficiency and leakage specifications for Energy Star duct systems and provide recommendations on duct insulation specifications. This analysis looks at a typical house, with a selection of duct locations, climates, duct insulation (R-value), and duct leakage. A set of calculations were performed with reduced capacity and airflow to look at the effect of variable capacity systems. This was done to address concerns regarding the increased efficiency of multi-capacity equipment due to good part load performance and how these efficiency gains may be offset by increased duct losses. The duct system efficiencies were calculated using the procedures in proposed ASHRAE Standard 152P "Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems" (ASHRAE 1999). This proposed ASHRAE Standard can be used to calculate duct efficiency for both design and seasonal weather conditions. In this report, the seasonal efficiencies are used for most of the analysis because they are the most appropriate for estimating energy consumption in buildings. The effects at peak conditions are examined for changing duct insulation in order to provide preliminary estimates of the potential responses to time of use pricing. The study was performed in two parts. The first part focused on duct leakage and the second part on duct insulation. The HVAC systems in the two parts share many attributes, however, they differ in detail and so are treated separately here. All the calculation results are summarized in tables in the Appendix, and specific results are given in the text.

Walker, I.S.; Sherman, M.H.; Wempen, J.; Wang, D.; McWilliams, J.A.; Dickerhoff, D.J. "Development of

a New Duct leakage Test: Delta Q." 2001. LBNL-47308 .

Abstract. Several studies (Francisco and Palmiter 1997 and 1999, Andrews et al. 1998, and Siegel et al. 2001) have shown that the duct system efficiency cannot be reliably determined without good estimates of duct leakage. Specifically, for energy calculations, it is the duct leakage air flow to outside at operating conditions that is required. Existing test methods either precisely measure the size of leaks (but not the flow through them at operating conditions), or measure these flows with insufficient accuracy. The DeltaQ duct leakage test method was developed to provide improved estimates of duct leakage during system operation. In this study we developed the analytical calculation methods and the test procedures used in the DeltaQ test. As part of the development process, we have estimated uncertainties in the test method (both analytically and based on field data) and designed automated test procedures to increase accuracy and reduce the contributions of operator errors in performing field tests. In addition, the test has been evaluated in over 100 houses by several research teams to show that it can be used in a wide range of houses and to aid in finding limits or problems in field applications. The test procedure is currently being considered by ASTM as an update of an existing duct leakage standard.

Walker, I.S.; Wray, C.P.; Dickerhoff, D.J.; Sherman, M.H. "Evaluation of flow hood measurements for residential register flows." 2001. LBNL-47382 .

Abstract. Flow measurement at residential registers using flow hoods is becoming more common. These measurements are used to determine if the HVAC system is providing adequate comfort, appropriate flow over heat exchangers and in estimates of system energy losses. These HVAC system performance metrics are determined by using register measurements to find out if individual rooms are getting the correct airflow, and in estimates of total air handler flow and duct air leakage. The work discussed in this paper shows that commercially available flow hoods are poor at measuring flows in residential systems. There is also evidence in this and other studies that flow hoods can have significant errors even when used on the non-residential systems they were originally developed for. The measurement uncertainties arise from poor calibrations and the sensitivity of exiting flow hoods to non-uniformity of flows entering the device. The errors are usually large – on the order of 20% of measured flow, which is unacceptably high for most applications. Active flow hoods that have flow measurement devices that are insensitive to the entering air flow pattern were found to be clearly superior to commercially available flow hoods. In addition, it is clear that current calibration procedures for flow hoods may not take into account any field application problems and a new flow hood measurement standard should be developed to address this issue.

Siegel, Jeffrey. "Fouling of HVAC fin and tube heat exchangers." 2001. LBNL-47668 .

Abstract. Fin and tube heat exchangers are used widely in residential, commercial and industrial HVAC applications. Invariably, indoor and outdoor air contaminants foul these heat exchangers. This fouling can cause decreased capacity and efficiency of the HVAC equipment as well as indoor air quality problems related to microbiological growth. This paper describes laboratory studies to investigate the mechanisms that cause fouling. The laboratory experiments involve subjecting a 4.7 fins/cm (12 fins/inch) fin and tube heat exchanger to an air stream that contains monodisperse particles. Air velocities ranging from 1.5 – 5.2 m/s (295 ft/min – 1024 ft/min) and particle sizes from 1 – 8.6 μm are used. The measured fraction of particles that deposit as well as information about the location of the deposited material indicate that particles greater than about 1 μm contribute to fouling. These experimental results are used to validate a model that describes the relative importance of several deposition mechanisms including impaction, Brownian diffusion, turbophoresis and gravitational settling. The analysis is extended to apply to different fin spacings and particle sizes typical of those found in indoor air.

Siegel, J.A.; Walker, I.S. "Deposition of biological aerosols on HVAC heat exchangers." 2001. LBNL-47669 .

Abstract. Many biologically active materials are transported as bioaerosols 1-10 μm in diameter. These particles can deposit on cooling and heating coils and lead to serious indoor air quality problems. This paper investigates several of the mechanisms that lead to aerosol deposition on fin and

tube heat exchangers. A model has been developed that incorporates the effects of several deposition mechanisms, including impaction, Brownian and turbulent diffusion, turbophoresis, thermophoresis, diffusiophoresis, and gravitational settling. The model is applied to a typical range of air velocities that are found in commercial and residential HVAC systems 1 – 6 m/s (200 – 1200 ft/min), particle diameters from 1 – 8 μm, and fin spacings from 3.2 – 7.9 fins/cm (8 – 16 fins/inch or FPI). The results from the model are compared to results from an experimental apparatus that directly measures deposition on a 4.7 fins/cm (12 FPI) coil. The model agrees reasonably well with this measured data and suggests that cooling coils are an important sink for biological aerosols and consequently a potential source of indoor air quality problems.

Carrie, F.R.; Modera, M.P. "Experimental investigation of aerosol deposition on slot-and joint-type leaks." Journal of Aerosol Science, Volume 33, Pages 1447-1462. 2001. LBNL-48774 .

Walker, I.S. "Assessing the longevity of residential duct sealants." Proceedings of the RILEM 3rd International Symposium, France, Pages 71-86, RILEM Publications S.A.R.I. Cachan Cedex, France. 2000. LBNL-43381 .

Walker, I.S.; Sherman, M.H.; Siegel, J.A.; Modera, M.P. "Effects of Duct Improvement and ENERGYSTAR Equipment on Comfort and Energy Efficiency." 2000. LBNL-43723 .

Abstract. Residential thermal distribution systems have significant energy and comfort implications due to losses from the distribution system in the form of leakage and conduction and poor distribution from room-to- room within the house. Also, poor mechanical equipment performance, and the interactions between the distribution system and the equipment act to further reduce system capacity and thermal comfort. An example of duct system and equipment interaction is the that airflow over the indoor coils changes the efficiency, capacity and humidity removal of the system resulting in comfort, energy consumption and efficiency changes. To determine if there are any differences in the interactions depending on whether or not the equipment is ENERGYSTAR rated, two houses were tested with standard (SEER10) air conditioners and then retrofitted with ENERGYSTAR (SEER 13) equipment. In addition, the effect of duct leakage was examined by adding leaks to the systems under test. The original plan had been to seal the duct systems, but they were found to be not very leaky. Leakage was added in order to show the effect of reduced leakage. Four additional houses were tested as part of a companion study (Walker et al. (1999)) that did not have equipment changes. Selected measurement results from these houses are presented where appropriate. This report is in two main parts. The first part discusses the field measurement techniques and results. The second part examines efforts to model distribution system performance using a sophisticated computer simulation program called REGCAP. REGCAP has been developed to specifically include the interactions of duct systems with their surroundings (In this study the duct surroundings are attic spaces). Lastly, a brief summary of related thermal distribution system research is included at the end of the report.

Siegel, J.A.; Walker, I.A.; Sherman, M.H. "Delivering Tons to the Register: Energy Efficient Design and Operation of Residential Cooling System." Proceedings of the ACEEE Summer Study 2000, Pacific Grove, CA, Volume 1, Pages 295-306, American Council for an Energy Efficient Economy, Washington, DC. 2000. LBL-45315.

Sherman, M.H.; Walker, I.S.; Dickerhoff, D.J. "Stopping Duct Quacks: Longevity of Residential Duct Sealants." Proceedings of the ACEEE 2000 Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 1, Pages 273-284, American Council for an Energy Efficient Economy, Washington, DC. 2000. LBNL-45423 .

Levinson, R.M.; Delp, W.W.; Dickerhoff, D.J.; Modera, M.P. "Effects of air infiltration on the effective thermal conductivity of internal fiberglass insulation and on the delivery of thermal capacity via ducts." 2000. LBNL-42499 .

Levinson, R.; Delp, W.; Dickerhoff, D.; Modera, M. "Effects of Airflow Infiltration on the Thermal Performance of Internally-insulated Ducts." Energy & Buildings, Volume 32, Pages 345-354. 2000. LBNL-45447.

Walker, I.S.; Sherman, M.H.; Siegel, J.A. "Distribution effectiveness and impacts on equipment sizing for residential thermal distribution systems." 1999. LBNL-43724 .

Abstract. Previous studies (including earlier phases of this research project) have shown that losses from residential thermal distribution systems have significant energy and comfort implications. This study looks at the potential for improvement of thermal distribution systems and the possibility of reducing equipment size as a result. These distribution system and equipment interactions were examined through field testing and computer simulation. In addition, this report outlines our efforts to transfer the results of this research to the marketplace so as to reduce energy losses and improve thermal comfort. This study describes the results of efforts made during the Transitional Phase of this Residential Thermal Distribution Systems research. Results of earlier Phases were described in Walker et al. (1997 and 1998).

Feustel, H.E. "COMIS – An International Multizone Air-Flow and Contaminant Transport Model." Energy and Buildings, Volume 30, Pages 3-18. 1999. LBNL-42182 .

Walker, I.S.; Modera, M.P. "Field Measurements of the Interactions between Furnaces and Forced Air Distribution Systems." ASHRAE Transactions, Volume 104, Pages 1805-1816. 1998. LBNL-40587 .

Abstract. Measurements on three gas and two electric furnaces have been made to examine the field performance of these furnaces and their interactions with their forced-air distribution systems. The distribution systems were retrofitted as part of this study and the impact of retrofitting on furnace performance is discussed. In addition to field measurements, this paper will discuss how forced-air furnace systems are treated in proposed ASHRAE Standard 152P, and applies the resulting equations to the systems tested in the field. The distribution system calculations in Standard 152P are compared to the current methods employed in the "Furnaces" chapter of ASHRAE's HVAC Systems and Equipment Handbook, showing how the distribution system efficiencies calculated using Standard 152P can be incorporated into the handbook.

Walker, I.; Sherman, M.; Modera, M.; Siegel, J. "Leakage Diagnostics, Sealant Longevity, Sizing and Technology Transfer in Residential Thermal Distribution Systems." 1998. LBNL-41118 .

Abstract. This field study concentrated on measurement of duct leakage to outside the conditioned space because this is most useful in energy calculations, e.g., proposed ASHRAE Standard 152P (ASHRAE 1997). For room by room load/comfort requirements, the total duct leakage (including leaks to conditioned space) is more appropriate, particularly for additional comfort considerations. The objective of this field study is to help to identify major sources of uncertainty and to quantify the trade-offs between different test methods. The identification of the areas requiring significant improvement will aid in future development of duct leakage test methods. For example, during the course of this study a new method for correcting house pressure tests to account for the presence of duct leakage in measured envelope leakage was developed. Each of the measurement techniques investigated has resulted from a different set of priorities and hence compromises. Thus each one of them is measuring a different physical quantity, although they all report the same parameter – duct leakage to outside at operating conditions. Given that real houses do not meet all of the simplifying assumptions that must be made to achieve similarity, the same numbers from each test method are not expected. Potentially these differences can be quite large and one of the benefits of field measurement is that the differences in the measurements helps put a realistic bound on how different some of these leakage diagnostics may be. To evaluate current duct leakage diagnostic methods, field tests were performed in 17 houses. The field tests were divided into two parts. The first part was performed in occupied S.F. Bay Area houses. The second part was performed in new unoccupied houses (some with unfinished interiors) in Irvine, CA. In the Bay Area, nine houses were tested using four diagnostic techniques.

Walker, I.; Siegel, J.; Brown, K.; Sherman, M. "Saving Tons at the Register." Proceedings of the 1998 ACEEE Summer Study on Energy Effciency in Buildings, Pacific Grove, CA, Volume 1, Pages 367-383, American Council for an Energy Efficient Economy, Washington, DC. 1998. LBNL-41957 .

Abstract. Duct losses have a significant effect on the efficiency of delivering space cooling to U.S. homes. This effect is especially dramatic during peak demand periods where half of the cooling

equipment's output can be wasted. Improving the efficiency of a duct system can save energy, but can also allow for downsizing of cooling equipment without sacrificing comfort conditions. Comfort, and hence occupant acceptability, is determined not only by steady-state temperatures, but by how long it takes to pull down the temperature during cooling start-up, such as when the occupants come home on a hot summer afternoon. Thus the delivered tons of cooling at the register during start-up conditions are critical to customer acceptance of equipment downsizing strategies. We have developed a simulation technique which takes into account such things as weather, heat-transfer (including hot attic conditions), airflow, duct tightness, duct location and insulation, and cooling equipment performance to determine the net tons of cooling delivered to occupied space. Capacity at the register has been developed as an improvement over equipment tonnage as a system sizing measure. We use this concept to demonstrate that improved ducts and better system installation is as important as equipment size, with analysis of pull-down capability as a proxy for comfort. The simulations indicate that an improved system installation including tight ducts can eliminate the need for almost a ton of rated equipment capacity in a typical new 2,000 square foot house in Sacramento, California. Our results have also shown that a good duct system can reduce capacity requirements and still provide equivalent cooling at start-up and at peak conditions.

Walker, I.S. "Technical Background for Default Values used for Forced Air Systems in Proposed ASHRAE Standard 152P." ASHRAE Transactions, Volume 104, Pages 1360-1375. 1998. LBNL-40588 .

Abstract. ASHRAE Standard 152P (Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems) includes default values for many of the input parameters required to calculate delivery system efficiencies. These default values have several sources: measured field data in houses, laboratory testing, simple heat transfer analyses, etc. This paper will document and discuss these default values and their sources for forced air systems.

Sherman, M.H.; Walker, I.S. "Can Duct-Tape Take the Heat?." Home Energy, Volume 15, Pages 14. 1998. LBNL-41434 .

Jump, D.A.; Walker, I.S.; Modera, M.P. "Field Measurements of Efficiency and Duct Retrofit Effectiveness in Residential Forced Air Distribution Systems." Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, Volume 1, Pages 147-156, American Council for an Energy Efficient Economy, Washington, DC. 1996. LBL-38537.

Abstract. Forced air distribution systems can have a significant impact on the energy consumed in residences. It is common practice in U.S. residential buildings to place such duct systems outside the conditioned space. This results in the loss of energy by leakage and conduction to the surroundings. In order to estimate the magnitudes of these losses, 24 houses in the Sacramento, California, area were tested before and after duct retrofitting. The systems in these houses included conventional air conditioning, gas furnaces, electric furnaces and heat pumps. The retrofits consisted of sealing and insulating the duct systems. The field testing consisted of the following measurements: leakage of the house envelopes and their ductwork, flow through individual registers, duct air temperatures, ambient temperatures, surface areas of ducts, and HVAC equipment energy consumption. These data were used to calculate distribution system delivery efficiency as well as the overall efficiency of the distribution system including all interactions with building load and HVAC equipment. Analysis of the test results indicate an average increase in delivery efficiency from 64% to 76% and a corresponding average decrease in HVAC energy use of 18%. This paper summarizes the pre- and post-retrofit efficiency measurements to evaluate the retrofit effectiveness, and includes cost estimates for the duct retrofits. The impacts of leak sealing and insulating will be examined separately.

Treidler, B.; Modera, M. "New Technologies for Residential HVAC Ducts." 1995. LBNL-35445 .

Modera, M.P.; Treidler, B. "Improved Modelling of HVAC System/Envelope Interactions in Residential Buildings." Proceedings of the ASME/JSME/JSES International Solar Energy Conference, Maui, HI, Volume 1, Pages 245-252, ASME, Washington, DC. 1995. LBL-36048.

3.6. Volatile Organic Compounds

Hodgson, A.T.; Levin, H. "Volatile organic compounds in indoor air: A review of concentrations measured in North America since 1990." Accepted for publication in Atmospheric Environment. 2003. LBNL-51715 .

Abstract. Central tendency and upper limit concentrations of volatile organic compounds (VOCs) measured in indoor air are summarized and reviewed. Data were obtained from published cross-sectional studies of residential and office buildings conducted in North America from 1990 through the present. VOC concentrations in existing residences reported in 12 studies comprise the majority of the data set. Central tendency and maximum concentrations are compared between new and existing residences and between existing residences and office buildings. Historical changes in indoor VOC concentrations since the Clean Air Act Amendments of 1990 are explored by comparing the current data set with two published reviews of previous data obtained primarily in the 1980s. These historical comparisons suggest average indoor concentrations of some toxic air contaminants, such as 1,1,1-trichloroethane have decreased.

Hodgson, A.T.; Levin, H. "Classification of measured indoor volatile organic compounds based on noncancer health and comfort considerations." To be submitted to Atmospheric Environment. 2003. LBNL-53308 .

Abstract. Building occupants are exposed to complex mixtures of air pollutants including many volatile organic compounds (VOCs). A recent review summarized the central tendency and upper limit indoor VOC concentrations measured in North American residences and office buildings since 1990. Although this database is limited in many respects, it serves as a useful starting point for evaluating the potential health and comfort effects of indoor VOC exposures. Excluding cancer and birth defects, the primary concern is chronic inhalation exposure to toxicants that can cause serious health problems. Additionally, building occupants react to the quality of indoor air through their sensory perceptions and frequently experience unpleasant odors and irritation of the eyes and upper respiratory tract. In this paper, we conduct a simple screening-level assessment of indoor VOC concentrations. We compare measured VOC concentrations to published odor thresholds, sensory irritation levels derived for the general population, and noncancer chronic health guidelines. Hazard quotients are individually calculated for these three effects by dividing maximum or derived 95th percentile VOC concentrations by our selected best estimates of guidance levels for the general population. These results provide a basis for broadly classifying commonly encountered VOCs into groups according to the likelihood that they will produce effects among building occupants. This methodology shows that only a small number of the more than 100 reported VOCs exceed levels that are likely to be of concern with respect to the health and comfort endpoints considered. Although data is lacking for a number of odorous compounds potentially present in buildings, the results indicate that carboxylic acids, higher molecular weight aldehydes and less volatile aromatic hydrocarbons are most likely to be perceived by olfaction and that there is more probability of detection in residences than in offices. Sensory irritation levels were approached or exceed by only a very small number of relatively potent, reactive VOCs. Of these, acrolein was by far the most potent irritant. Although more detailed consideration of the underlying toxicological data is needed, the results suggest that only a small number of commonly measured VOCs, when considered singly, are likely to produce serious irreversible health effects not associated with cancer. These compounds include lower molecular weight aldehydes, and several aromatic hydrocarbons. Again, acrolein stands out as the most potent compound. Based on these results, we recommend that studies to characterize indoor VOC concentrations and exposures focus their resources on compounds that are most likely to impact occupants as determined by the study objectives. For a very few compounds, such as acrolein and formaldehyde, the evidence based on sensory irritation and chronic toxicity appears sufficient to warrant efforts to reduce and control sources of these compounds in buildings.

Hodgson, A.T. "Volatile organic chemical emissions from structural insulated panel (SIP) materials and implications for indoor air quality." To be submitted to Atmospheric Environment. 2003. LBNL-53768 .

Abstract. The emissions of volatile organic compounds (VOCs) from structural insulated panel (SIP) materials were investigated. Specimens of newly produced SIPs and associated panel adhesives were obtained from two relatively large manufacturers. Additionally, specimens of the oriented strand board (OSB) used as the inner and outer sheathing and the extruded polystyrene ore for the SIP were obtained from one manufacturer. Using small-scale chambers, emissions of formaldehyde,

acetaldehyde, acetic acid and other VOCs from SIPs, OSB and polystyrene were measured over a period of four months and from the adhesives over two months. SIP specimens overlaid by gypsum board panels were also tested over four months. The predominant VOCs emitted by the SIPs included acetic acid, pentanal, hexanal and styrene. The emissions of formaldehyde and acetaldehyde were relatively low. Acetic acid and the aldehydes derived from the OSB, while styrene derived from the polystyrene. One of the SIPs emitted toluene and methyl acetate. The adhesives primarily emitted a mixture of hydrocarbons. The emission rates of most VOCs from the SIP/gypsum board assemblies were approximately the same or higher than their respective emission rates from the unfinished SIPs. Modeling using VOC emission factors obtained for the SIP/gypsum board assemblies demonstrated the potential for SIP materials to degrade indoor air quality in houses. A field study to investigate VOC concentrations and emission rates in SIP houses relative to closely matched conventionally constructed houses is necessary to determine the actual impacts of SIPs. If significant impacts are observed, to it may be desirable to develop control measures to reduce the emissions of VOCs from SIPs, such as the substitution of lower emitting materials or the use of vapor diffusion barriers.

Zhao, D; Little, J.C.; Hodgson, A.T. "Modeling the Reversible Sink Effect in Response to Transient Contaminant Sources." Indoor Air, Volume 12, Pages 184-190. 2002. LBNL-47095 .

Abstract. A physically based diffusion model is used to evaluate the sink effect of diffusion-controlled indoor materials and to predict the transient contaminant concentration in indoor air in response to several time-varying contaminant sources. For simplicity, it is assumed that the predominant indoor material is a homogeneous slab, initially free of contaminant, and that the air within the room is well mixed. The model enables transient volatile organic compound (VOC) concentrations to be predicted based on the material/air partition coefficient (K) and the material-phase diffusion coefficient (D) of the sink. Model predictions are made for four scenarios, each mimicking a realistic situation in a building. Styrene, phenol, and naphthalene are used as representative VOCs. A styrene butadiene rubber (SBR) backed carpet, vinyl flooring (VF), and a polyurethane foam (PUF) carpet cushion are considered as typical indoor sinks. In scenarios involving a sinusoidal VOC input and a double exponential decaying input, the model predicts that the sink has a modest impact for SBR/styrene, but that the effect increases for VF/phenol and PUF/naphthalene. In contrast, for an episodic chemical spill, SBR is predicted to reduce the peak styrene concentration considerably. A parametric study reveals that for systems involving a high equilibrium factor (K), the kinetic factor (D) will govern the shape of the resulting gas-phase concentration profile. On the other hand, for systems with a relaxed mass transfer resistance, K will dominate the profile.

Hodgson, A.T.; Beal, D.; McIlvaine, J.E.R. "Sources of formaldehyde, other aldehydes and terpenes in a new manufactured house." Indoor Air, Volume 12, Pages 235-242. 2002. LBNL-47627 .

Abstract. ABSTRACT Formaldehyde, less-volatile aldehydes, and terpene hydrocarbons are generally the predominant air contaminants in new manufactured and site-built houses. This study was conducted to identify the major sources of these compounds in a typically constructed, new manufactured house. Specimens of materials used within the house envelope were collected from the production facility. These were individually preconditioned for 19 $\pm$ 4 days and tested for emissions of formaldehyde and the other target compounds using small-scale chambers. Several cabinetry materials, passage doors and the plywood subfloor were the predominant sources of formaldehyde and other aldehydes. The plywood subfloor was the predominant terpene source. Whole-house emission rates for combined materials were predicted based on the emission factors and the corresponding material quantities. These predicted rates were compared to whole-house emission rates calculated from measurements made at the house three months after its installation. For 11 of 14 target compounds including formaldehyde, the predicted and calculated rates were within a factor of two. This generally good agreement indicates that the predominant sources were correctly accounted for. Based on these results, practices are proposed for reducing the concentrations of the target compounds in newly constructed houses.

Cox, S.S.; Little, J.C.; Hodgson, A.T. "Predicting the emission rate of volatile organic compounds from

vinyl flooring." Environmental Science & Technology, Volume 36, Pages 709-714. 2002. LBNL-47094 .

Abstract. A model for predicting the rate at which a volatile organic compound (VOC) is emitted from a diffusion- controlled material is validated for three contaminants (n-pentadecane, n-tetradecane, and phenol) found in vinyl flooring (VF). Model parameters are the initial VOC concentration in the material-phase (C0), the material/air partition coefficient (K), and the material-phase diffusion coefficient (D). The model was verified by comparing predicted gas-phase concentrations to data obtained during small-scale chamber tests, and by comparing predicted material-phase concentrations to those measured at the conclusion of the chamber tests. Chamber tests were conducted with the VF placed top side up and bottom side up. With the exception of phenol, and within the limits of experimental precision, the mass of VOCs recovered in the gas phase balances the mass emitted from the material phase. The model parameters (C0, K, and D) were measured using procedures that were completely independent of the chamber test. Gas- and material-phase predictions compare well to the bottom-side-up chamber data. The lower emission rates for the top-side-up orientation may be explained by the presence of a low-permeability surface layer. The sink effect of the stainless steel chamber surface was shown to be negligible.

Bennett, D.H.; Furtaw, E.J.; McKone, T.E. "A fugacity-based indoor residential pesticide fate model." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 261-266, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-53458 .

Abstract. Dermal and non-dietary pathways are potentially significant exposure pathways to pesticides used in residences. Exposure pathways include dermal contact with residues on surfaces, ingestion from hand- and object-to-mouth activities, and absorption of pesticides into food. A limited amount of data has been collected on pesticide concentrations in various residential compartments following an application. But models are needed to interpret this data and make predictions about other pesticides based on chemical properties. In this paper, we propose a mass-balance compartment model based on fugacity principles. We include air (both gas phase and aerosols), carpet, smooth flooring, and walls as model compartments. Pesticide concentrations on furniture and toys, and in food, are being added to the model as data becomes available. We determine the compartmental fugacity capacity and mass transfer-rate coefficient for wallboard as an example. We also present the framework and equations needed for a dynamic mass- balance model.

Cox, S.S.; Hodgson, A.T.; Little, J.C. "Measuring Concentrations of Volatile Organic Compounds in Vinyl Flooring." Journal of the Air & Waste Management Association, Volume 51, Pages 174-185. 2001. LBNL-47086 .

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Little, J.C.; Hodgson, A.T. "A Strategy for Characterizing Homogeneous, Diffusion-Controlled, Indoor Sources and Sinks." ASTM STP 1287, Characterizing Sources of Infoor Air Pollution and Related Sink Effects, Pages 294-304, American Society for Testing and Materials. 1996.

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4. Indoor Airflow and Pollutant Transport

Sippola, M.R.; Nazaroff, W.W. "Particle Deposition in Ventilation Ducts: Connectors, Bends and Developing Flow." To be submitted to Aerosol Science and Technology. 2004. LBNL-54843 .

Abstract. In ventilation duct flow the turbulent flow profile is commonly disturbed or not fully developed and these conditions are likely to influence particle deposition to duct surfaces. Particle deposition rates at eight S-connectors, in two 90° duct bends and in two ducts where the turbulent flow profile was not fully developed were measured in a laboratory duct system with both galvanized steel and internally insulated ducts with hydraulic diameters of 15.2 cm. In the steel duct system, experiments with nominal particle diameters of 1, 3, 5, 9 and 16 μm were conducted at each of three nominal air speeds: 2.2, 5.3 and 9.0 m/s. In the insulated duct system, deposition of particles with nominal diameters of 1, 3, 5, 8 and 13 μm was measured at nominal air speeds of 2.2, 5.3 and 8.8 m/s. Fluorescent techniques were used to directly measure the deposition velocities of monodisperse fluorescent particles to duct surfaces. Deposition at S-connectors, in bends and in straight ducts with developing turbulence was often greater than deposition in straight ducts with fully developed turbulence for equal particle sizes, air speeds and duct surface orientations. Deposition rates at all locations were found to increase with an increase in particle size or air speed. High deposition rates at S-connectors resulted from impaction and these rates were nearly independent of the orientation of the S-connector. Deposition rates in the two 90° bends differed by more than an order of magnitude in some cases, probably because of the difference in turbulence conditions at the bend inlets. In straight steel ducts where the turbulent flow profile was developing, the deposition enhancement relative to fully developed turbulence generally increased with air speed and decreased with downstream distance from the duct inlet. This enhancement was greater at the duct ceiling and wall than at the duct floor. In insulated ducts, deposition enhancement was less pronounced overall than in steel ducts. Trends that were observed in steel ducts were present, but weaker, in insulated ducts.

Price, P. N.; Chang, S.C.; Sohn, M.D. "Characterizing buildings for airflow models: What should we measure?." Submitted to RoomVent 2004 - 9th International Conference on Air Distribution in Rooms, Coimbra, Portugal. 2004. LBNL-55321 .

Abstract. Airflow models of buildings require dozens to hundreds of parameter values, depending on the complexity of the building and the level of fidelity desired for the model. Values for many of the parameters are usually subject to very large uncertainties (possibly an order of magnitude). Experiments can be used to calibrate or "tune" the model: input parameters can be adjusted until predicted quantities match observations. However, experimental time and equipment are always limited and some parameters are hard to measure, so it is generally impractical to perform an exhaustive set of measurements. Consequently, large uncertainties in some parameters typically remain even after tuning the model. We propose a method to help determine which measurements will maximally reduce the uncertainties in those input parameters that have the greatest influence on behavior of interest to researchers. Implications for experimental design are discussed.

Levin, H. "Indoor Air Pollutants Part 2: Description of sources and control/mitigation measures." Air Infiltration and Ventilation Centre, Pages 1-8. 2004. LBNL-55774 .

Abstract. This Ventilation Information Paper (VIP) addresses the sources of pollutants and effective measures to control them or to mitigate their impacts on occupants and building contents. The most effective means to control indoor air pollution is through reduction or elimination of pollution sources. Indoor pollutants originate both within the building and from outside. The first step in controlling the sources of indoor air pollution is to identify them. Building materials, occupants and their activities, and equipment and appliances can all be sources of indoor pollutants. Once the sources have been identified, control strategies can be developed and implemented. Appropriate ventilation strategies can reduce concentrations of pollutants that can't be eliminated by source control. Air cleaning and filtration can reduce the concentrations of contaminants in buildings where ventilation systems recirculate air within the building.

Kristoffersen, A.R.; Gadgil, A.; Lorenzetti, D. "Effect of room air recirculation delay on the decay rate of tracer gas." Submitted to RoomVent 2004, Coimbra, Portugal. 2004. LBNL-55083 .

Jayaraman, B.; Kristoffersen, A.R.; Finlayson, E.O.; Gadgil, A. "Investigation of Room Ventilation for Improved Operation of a Downdraft Table." To be published in Proceedings of Room Vent 2004, Coimbra, Portugal.. 2004. LBNL-55561 .

Abstract. We report a computational fluid dynamics (CFD) study on containment of airborne hazardous materials in a ventilated room containing a downdraft table. Specifically, we investigate the containment of hazardous airborne material obtainable under a range of ventilation configurations. The desirable ventilation configuration should ensure excellent containment of the hazardous material released from the workspace above the downdraft table. However, increased airflow raises operation costs, so the airflow should be as low as feasible without compromising containment. The airflow is modeled using Reynolds Averaged Navier Stokes equations with a high Reynolds number k-epsilon turbulence model. CFD predictions are examined for several ventilation configurations. Based on this study, we find that substantial improvements in containment are possible concurrent with a significant reduction in airflow, compared to the existing design of ventilation configuration.

Chan, W.R.; Price, P. N.; Gadgil, A.J. "Sheltering in buildings from large-scale outdoor releases." 2004. LBNL-55575 .

Abstract. Intentional or accidental large-scale airborne toxic release (e.g. terrorist attacks or industrial accidents) can cause severe harm to nearby communities. Under these circumstances, taking shelter in buildings can be an effective emergency response strategy. Some examples where shelter-in-place was successful at preventing injuries and casualties have been documented [1, 2]. As public education and preparedness are vital to ensure the success of an emergency response, many agencies have prepared documents advising the public on what to do during and after sheltering [3, 4, 5]. In this document, we will focus on the role buildings play in providing protection to occupants.

Thatcher, T.L.; D.J. Wilson; E.E. Wood; M.J. Craig; R.G. Sextro. "Pollutant Dispersion in a Large Indoor Space: Part 1 – Scaled experiments using a water-filled model with occupants and furniture." Submitted to Indoor Air. 2003. LBNL-50248 .

Abstract. Pollutant dispersion experiments were performed in a water-filled 30:1 scale model of a large room. Theoretical calculations were performed to confirm that the effects from losses of molecular diffusion, small scale eddies, turbulent kinetic energy, and turbulent mass diffusivity were minimal, even without matching Reynolds number between model and full scale. In the experiments, uranine dye was injected continuously from a small point source near the floor of the model. Pollutant concentrations were measured in a plane using laser induced fluorescence techniques. The concentration profiles were measured for three interior configurations for the model: unobstructed, table-like obstructions, and table- like and figure-like obstructions. The presence of objects in the model interior had a significant effect of both the concentration profile and fluctuation intensity in the measurement plane.

Mora, L.; Gadgil, A.J.; Wurtz, E. "Comparing zonal and CFD models of air flows in large indoor spaces to experimental data." Indoor Air, Volume 13, Pages 77-85. 2003. LBNL-47027 .

Abstract. It is inappropriate to use the assumption of instantaneously well-mixed zones to model airflows and pollutant transport in large indoor spaces. We investigate two approaches for describing the details of airflows in large indoor spaces, for accuracy and suitability for integration with multi-zone infiltration models. One approach, called the zonal method, was developed over the last 15 years to provide an improvement over the well-mixed assumption. The second approach is the use of a computational fluid dynamics simulation using a coarse grid model of the large indoor space. We compare velocity predictions from different formulations of zonal methods and coarse-grid k-e computational fluid dynamics (CFD) models, to measurements, in a 2D mechanically ventilated isothermal room. Our results suggest that, when airflow details are required, coarse-grid CFD is a better-suited method to predict airflows in large indoor spaces coupled with complex multi-zone buildings, than are the zonal methods. Based on the comparison of pressure predictions from different models, we offer guidance regarding the coupling of a model of detailed airflow in large spaces to algebraic multi-zone infiltration models.

Levin, H. "Indoor Air Pollutants Part 1: General description of pollutants, levels and standards." Air Infiltration and Ventilation Centre, Pages 1-12. 2003. LBNL-55772 .

Abstract. Pollutants found in indoor air are often several times higher than outdoors. Indoor air pollutants cause effects ranging from odor, annoyance, and irritation to illness, cancer, and even death. Since people spend the majority of their time indoors, it is important to recognize and control indoor air pollution. Some indoor air pollutants also adversely affect materials in the building and the building structure itself. The majority of indoor pollution comes from the building itself, its contents, or its occupants and their activities. Building materials and consumer products are important sources of indoor air pollutants. Some outdoor air pollutants enter with ventilation air. Interactions between substances in indoor air can also produce pollutants and some of these are more odorous, irritating, or hazardous than the chemicals that forms them. Reducing or eliminating pollution sources best achieves control of indoor air quality. Appropriate ventilation strategies can reduce concentrations of pollutants that can't be eliminated by source control.

Gadgil, A.J.; Lobscheid, C.; Abadie, M.O.; Finlayson, E.U. "Indoor Pollutant Mixing Time in an Isothermal Closed Room: An investigation using CFD." Atmospheric Environment, Volume 37, Pages 5577-5586. 2003. LBNL-51413 .

Abstract. We report computational fluid dynamics (CFD) predictions of mixing time of a point pulse release of a pollutant in an unventilated mechanically mixed isothermal room. The aims of the study are to determine (1) the adequacy of the standard RANS two-equation (k-?) turbulence model to predict the mixing times under these conditions, and (2) the extent to which the mixing time is a feature of the room airflow, rather than the source location within the room. CFD simulations modeled the twelve mixing time experiments performed by Drescher et al. (1995) in an isothermal sealed room for a point pulse release. Predictions of mixing time were found in good agreement with experimental measurements, over an order of magnitude variation in blower power. Additional CFD simulations were performed to investigate the relation between pollutant mixing time and pollutant source location. Seventeen source locations were investigated for five different blower power configurations in the room. Results clearly show large dependence of the mixing time on the room airflow, with some dependence on source location. We further explore dependence of mixing time on the local airflow properties (velocity and turbulence intensity) at the source location. Implications for our findings for positioning air-toxic sensors in rooms are also discussed.

Finlayson, E.U.; Jayaraman, B.; Kristoffersen, A.R.; Gadgil, A.J. "CFD Analysis of LLNL downdraft table." 2003. LBNL-53883 .

Abstract. This study examines the airflow and contaminant transport in an existing room (89"x77"x98") that houses a downdraft table at LLNL. The facility was designed and built in the 1960's and is currently being considered for redesign. One objective of the redesign is to reduce airflow while maintaining or improving user safety. Because this facility has been used for many years to handle radioactive material it is impractical to conduct extensive experimental tests in it. Therefore, we have performed a Computational Fluid Dynamic (CFD) analysis of the facility. The study examines the current operational condition and some other cases with reduced airflow. Reducing airflow will lead to savings in operating costs (lower fan power consumption), and possible improvements in containment from reduced turbulence. In addition, we examine three design (geometry) changes. These are: (1) increasing the area of the HVAC inlet on the ceiling, (2) adding a 15? angled ceiling inlet and (3) increasing the area of the slot in the doorway. Of these three geometry modifications, only the larger doorway slot leads to improved predicted containment.

Finlayson, E.U.; Gadgil, A.J.; Thatcher, T.L.; Sextro, R.G. "Pollutant Dispersion in a Large Indoor Space Part 2 – Computational Fluid Dyamics (CF) Predictions and Comparisons with a Model Experiment for Isothermal Flow." Accepted for publication in Indoor Air. 2003. LBNL-50105 .

Abstract. This paper reports on an investigation of the adequacy of Computational fluid dynamics (CFD), using a standard Reynolds Averaged Navier Stokes (RANS) model, for predicting dispersion of neutrally buoyant gas in a large indoor space. We used CFD to predict pollutant (dye) concentration profiles in a water filled scale model of an atrium with a continuous pollutant source.

Predictions from the RANS formulation are comparable to an ensemble average of independent identical experiments. Model results were compared to pollutant concentration data in a horizontal plane from experiments in a scale model atrium. Predictions were made for steady-state (fully developed) and transient (developing) pollutant concentrations. Agreement between CFD predictions and ensemble averaged experimental measurements is quantified using the ratios of CFD-predicted and experimentally measured dye concentration at a large number of points in the measurement plane. Agreement is considered good if these ratios fall between 0.5 and 2.0 at all points in the plane. The standard k-epsilon two equation turbulence model obtains this level of agreement and predicts pollutant arrival time to the measurement plane within a few seconds. These results suggest that this modeling approach is adequate for predicting isothermal pollutant transport in a large room with simple geometry.

Sohn, M.D.; Reynolds, P.; Gadgil, A.J.; Sextro, R.G. "Rapidly Locating Sources And Predicting Contaminant Dispersion In Buildings." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 4, Pages 211-216, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49563 .

Abstract. Contaminant releases in or near a building can lead to significant human exposures unless prompt response measures are taken. However, selecting the proper response depends in part on knowing the source locations, the amounts released, and the dispersion characteristics of the pollutants. We present an approach that estimates this information in real time. It uses Bayesian statistics to interpret measurements from sensors placed in the building yielding best estimates and uncertainties for the release conditions, including the operating state of the building. Because the method is fast, it continuously updates the estimates as measurements stream in from the sensors. We show preliminary results for characterizing a gas release in a three-floor, multi-room building at the Dugway Proving Grounds, Utah, USA.

Sohn, M.D.; Reynolds, P.; Singh, N.; Gadgil, A.J. "Rapidly locating and characterizing pollutant releases in buildings: An application of Bayesian data analysis." Journal of the Air and Waste Management Association, Volume 52, Pages 1422-1432. 2002. LBNL-47588.

Abstract. Releases of airborne contaminants in or near a building can lead to significant human exposures unless prompt response measures are taken. However, possible responses can include conflicting strategies, such as shutting the ventilation system off versus running it in a purge mode, or having occupants evacuate versus sheltering in place. The proper choice depends in part on knowing the source locations, the amounts released, and the likely future dispersion routes of the pollutants. We present an approach that estimates this information in real time. It applies Bayesian statistics to interpret measurements of airborne pollutant concentrations from multiple sensors placed in the building and computes best estimates and uncertainties of the release conditions. The algorithm is fast, capable of continuously updating the estimates as measurements stream in from sensors. We demonstrate the approach using a hypothetical pollutant release in a five-room building. Unknowns to the interpretation algorithm include location, duration, and strength of the source, and some building and weather conditions. We examine two sensor sampling plans and three levels of data quality. Data interpretation in all examples is rapid; however, locating and characterizing the source with high probability depends on the amount and quality of data, and the sampling plan.

Sextro, R.G.; Lorenzetti, D.M.; Sohn, M.D.; Thatcher, T.L. "Modeling the spread of anthrax in buildings." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 4, Pages 506-511, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49537 .

Abstract. The recent contamination of several U.S. buildings by letters containing anthrax demonstrates the need to understand better the transport and fate of anthrax spores within buildings. We modeled the spread of anthrax for a hypothetical office suite and estimated the distribution of mass and resulting occupant exposures. Based on our modeling assumptions, more than 90% of the anthrax released remains in the building during the first 48 hours, with the largest fraction of the mass accumulating on floor surfaces where it is subject to tracking and resuspension. Although tracking and resuspension account for only a small amount of mass transfer, the model results suggests they can have an important effect on subsequent exposures. Additional research is necessary

to understand and quantify these processes.

Lorenzetti, D.M. "Assessing multizone airflow simulation software." Proceedings of the Indoor Air 2002, Monterey, CA, Volume 1, Pages 267-271, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49578 .

Abstract. Several standard multizone modeling programs, in order to improve their computational efficiency, make a number of simplifying assumptions. This paper examines how those assumptions reduce the solution times and memory use of the programs, but at the cost of restricting the models they can express. Applications where these restrictions may adversely affect the program's usefulness include: (1) natural ventilation, when buoyancy effects dominate mechanically-driven flow; (2) duct system design, when losses in T- junctions affect the system performance; and (3) control system design, when the dynamic transport of pollutants plays a significant role in the simulated system.

Lorenzetti, D.M. "Computational Aspects of Nodal Multizone Airflow Systems." Building and Environment, Volume 37, Pages 1083-1090. 2002. LBNL-46949.

Abstract. The multizone approach to steady-state airflow problems models a building as a network of discrete mass flow paths. A nodal formulation of the problem writes the governing equations in terms of the unknown pressures at the points where the flow paths connect. This paper proves conditions under which the nodal equations yield symmetric positive-definite matrices, guaranteeing a unique solution to the flow network. It also establishes relaxed conditions under which a nodal airflow system yields asymmetric matrices with positive eigenvalues, guaranteeing at least one solution. Properly exploiting the system properties greatly reduces the cost of numerical solution. Thus, multizone airflow programs such as Contam and Comis depend on symmetric positive-definite systems. However, the background literature neglects or simplifies the underlying assumptions, does not assert existence and uniqueness, and even contains factual errors. This paper corrects those errors, states the implicit assumptions made in the programs, and discusses implications for modelers and programmers.

Lorenzetti, D.M. "Predicting Indoor Pollutant Concentrations, and Applications to Air Quality Management." Proceedings of the Joint WHO-JRC-ECA Workshop on the Role of Human Exposure Assessment in Air Quality Management, Bonn, Germany. 2002. LBNL-51582 .

Abstract. Because most people spend more than 90% of their time indoors, predicting exposure to airborne pollutants requires models that incorporate the effect of buildings. Buildings affect the exposure of their occupants in a number of ways, both by design (for example, filters in ventilation systems remove particles) and incidentally (for example, sorption on walls can reduce peak concentrations, but prolong exposure to semivolatile organic compounds). Furthermore, building materials and occupant activities can generate pollutants. This paper surveys modeling approaches for predicting pollutant concentrations in buildings, and summarizes the application of these models.

Lobscheid, C.; Gadgil, A. J. "Mixing of a point-source indoor pollution: Numerical predictions and comparison with experiments." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 4, Pages 223-228, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49457 .

Abstract. In most practical estimates of indoor pollutant exposures, it is common to assume that the pollutant is uniformly and instantaneously mixed in the indoor space. It is also commonly known that this assumption is simplistic, particularly for point sources, and for short-term or localized indoor exposures. We report computational fluid dynamics (CFD) predictions of mixing time of a point-pulse release of a pollutant in an unventilated mechanically mixed isothermal room. We aimed to determine the adequacy of the standard RANS two-equation (k-?) turbulence model to predict the mixing times under these conditions. The predictions were made for the twelve mixing time experiments performed by Drescher et al. (1995). We paid attention to adequate grid resolution, suppression of numerical diffusion, and careful simulation of the mechanical blowers used in the experiments. We found that the predictions are in good agreement with experimental measurements.

Fischer, M. L.; Price, P. N.; Thatcher, T. L.; Schwalbe, C. A.; Craig, M. J.; Wood, E. E.; Sextro, R. G.; Gadgil, A. J. "Rapid Measurement and Mapping of Tracer Gas Concentrations in a Large Indoor Space."

Atmospheric Environment, Volume 35, Pages 2837-2844. 2002. LBNL-45542 .

Abstract. Rapid mapping of gas concentrations in air benefits studies of atmospheric phenomena ranging from pollutant dispersion to surface layer meteorology. Here we demonstrate a technique that combines multiple-open-path tunable-diode-laser (TDL) spectroscopy and computed tomography to map tracer gas concentrations with approximately 0.5 m spatial and 7 second temporal resolution. Releasing CH4 in a large (7m x 9m x 11m high) ventilated chamber, we measured path-integrated CH4 concentrations over a planar array of 28 "long" (2-10 m) optical paths, recording a complete sequence of measurements every 7 seconds during the course of hour-long experiments. Maps of CH4 concentration were reconstructed from the long-path data and compared with simultaneous measurements from 28 "short" (0.5 m) optical paths. On average, the reconstructed maps capture 74% of the variance in the short path measurements. The accuracy of the reconstructed maps is limited, in large part, by the number of optical paths and the time required for the measurement. Straightforward enhancements to the instrumentation will allow rapid mapping of three-dimensional gas concentrations in indoor and outdoor air, with sub-second temporal resolution.

Federspiel, C.; H. Li; Auslander, D.; Lorenzetti, D.M.; Gadgil, A. J. "Modeling transient contaminant transport in HVAC systems and buildings." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 4, Pages 217-222, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49603 .

Abstract. A mathematical model of the contaminant transport in HVAC systems and buildings is described. The model accounts for transients introduced by control elements such as fans and control dampers. The contaminant transport equations are coupled to momentum equations and mass continuity equations of the air. To avoid modeling variable transport delays directly, ducts are divided into a large number of small sections. Perfect mixing is assumed in each section. Contaminant transport equations are integrated with momentum equations in a way that guarantees mass continuity by using two non-negative velocities for computing the mass transport between elements. Computer simulations illustrate how the model may be used to analyze and design control systems that respond to a sudden release of a toxic contaminant near a building. By coupling transient flow prediction with transient contaminant prediction, the model overcomes a number of problems with existing contaminant transport codes.

Lorenzetti, D.M. "Assessing Multizone Airflow Software." 2001. LBNL-47653 .

Abstract. Multizone models form the basis of most computer simulations of airflow and pollutant transport in buildings. In order to promote computational effciency, some multizone simulation programs, such as COMIS and CONTAM, restrict the form that their flow models may take. While these tools allow scientists and engineers to explore a wide range of building airflow problems, increasingly their use has led to new questions not answerable by the current generation of programs. This paper, directed at software developers working on the next generation of building airflow models, identifies structural aspects of COMIS and related programs that prevent them from easily incorporating desirable new airflow models. The paper also suggests criteria for evaluating alternate simulation environments for future modeling efforts.

Liu, D.L.; Nazaroff, W.W. "Modeling pollutant penetration across building envelopes." Atmospheric Environment, Volume 35, Pages 4451-4462. 2001. LBNL-47785 .

Sohn, M.D.; Small, M.J.; Pantazidou, M. "Reducing uncertainty in site characterization using Bayes Monte Carlo methods." Journal of Environmental Engineering, Volume 126, Pages 893-902. 2000. LBNL-48043.

Abstract. A Bayesian uncertainty analysis approach is developed as a tool for assessing and reducing uncertainty in ground-water flow and chemical transport predictions. The method is illustrated for a site contaminated with chlorinated hydrocarbons. Uncertainty in source characterization, in chemical transport parameters, and in the assumed hydrogeologic structure was evaluated using engineering judgment and updated using observed field data. The updating approach using observed hydraulic head data was able to differentiate between reasonable and unreasonable hydraulic conductivity fields but could not differentiate between alternative conceptual models for the geological structure of the subsurface at the site. Updating using observed chemical concentration

data reduced the uncertainty in most parameters and reduced uncertainty in alternative conceptual models describing the geological structure at the site, source locations, and the chemicals released at these sources. Thirty-year transport projections for no-action and source containment scenarios demonstrate a typical application of the methods.

Robinson, A.L.; Sextro, R.G. "A novel technique to measure the magnitude and direction of flow in a tube." Journal of Fluids Engineering, Volume 122, Pages 186-188. 2000.

Price, P.N.; Fischer, M.L.; Gadgil, A.J.; Sextro, R.G. "Algorithm for rapid tomography of gas concentrations." Atmospheric Environment, Volume 35, Pages 2827-2835. 2000. LBNL-46236.

Lorenzetti, D.M.; Sohn M.D. "Improving Speed and Robustness of the COMIS Solver." Proceedings of the RoomVent 2000,7th International Conference on Air Distribution in Rooms, Reading, UK, Volume 1, Pages 241-246, The University of Reading, P.O. Box 219, Whiteknights, Reading RG6 6AW, United Kingdom. 2000. LBL-44792 .

Abstract. The numerical investigation of airflow and chemical transport characteristics for a general class of buildings involves identifying values for model parameters, such as effective leakage areas and temperatures, for which a fair amount of uncertainty exists. A Monte Carlo simulation, with parameter values drawn from likely distributions using Latin Hypercube sampling, helps to account for these uncertainties by generating a corresponding distribution of simulated results. However, conducting large numbers of model runs can challenge a simulation program, not only by increasing the need for fast algorithms, but also by proposing specific combinations of parameter values that may define difficult numerical problems. The paper describes several numerical approaches to improving the speed and reliability of the COMIS multizone airflow simulation program. Selecting a broad class of algorithms based on the mathematical properties of the airflow systems (symmetry and positive-definiteness), it evaluates new solution methods for possible inclusion in the COMIS code. In addition, it discusses further changes that will likely appear in future releases of the program.

Gadgil, A.G.; Finlayson, E.U.; Fischer, M.L.; Price, P.N.; Thatcher, T.L.; Craig, M.J.; Hong, K.H.; Housman, J.; Schwalbe, C.A.; Wilson, D.; Wood, E.E.; Sextro, R.G. "Pollutant transport and dispersion in large indoor spaces: A status report for the large space effort of the Interiors Project." 2000. LBNL-44791 .

Thatcher, T.L.; Fischer, M.L.; Price, P.N.; Fisk, W.J.; Gadgil, A.J.; Sextro, R.G. "Measuring dispersion of gases in a large scale indoor environment using an open path tunable diode laser." Proceedings of the Indoor Air '99, Edinburgh, Scotland, Volume 4, Pages 449-450, Construction Research Communications, Ltd., London. 1999. LBNL-42714.

Sohn, M.D.; A. Lai; B.V. Smith; R.G. Sextro; H.E. Feustel; W.W. Nazaroff. "Modeling aerosol behavior in multizone indoor environments." Proceedings of the Indoor Air '99, Edinburgh, Scotland, Volume 4, Pages 785-790, Construction Research Communications, Ltd., London. 1999. LBNL-42708.

Abstract. A publicly available aerosol dynamics model, MIAQ4, is coupled to a widely used multizone air flow and transport model, COMIS, to better understand and quantify the behavior of particles in indoor environments. MIAQ4 simulates the evolution of a size and chemically resolved particle distribution, including the effects of direct indoor emission, ventilation, filtration, deposition, and coagulation. COMIS predicts interzonal air-exchange rates based on pressure gradients (due to wind, buoyancy, and HVAC operation) and leaks between the zones and with the outside. The capabilities of the coupled system are demonstrated by predicting the transport of particles from two sources in a residence: environmental tobacco smoke (ETS) and particles generated from cooking. For ETS, MIAQ4 predicts particle size distributions that are similar to the emission source profile because ETS particles, concentrated in the size range 0.1 – 1 ?m, are transformed by coagulation and deposition slowly compared with the rates of transport. For cooking, MIAQ4 predicts that the larger-sized particles will settle rapidly, causing a shift in size distribution as emissions are transported to other rooms.

Sohn, M.D.; J.M. Daisey; H.E. Feustel. "Characterizing indoor airflow and pollutant transport using simulation modeling for prototypical buildings. 1. Office buildings." Proceedings of the Indoor Air '99, Edinburgh,

Scotland, Volume 4, Pages 719-724, Construction Research Communications, Ltd., London. 1999. LBNL-42712.

Abstract. This paper describes the first efforts at developing a set of prototypical buildings defined to capture the key features affecting airflow and pollutant transport in buildings. These buildings will be used to model airflow and pollutant transport for emergency response scenarios when limited site-specific information is available and immediate decisions must be made, and to better understand key features of buildings controlling occupant exposures to indoor pollutant sources. This paper presents an example of this approach for a prototypical intermediate-sized, open style, commercial building. Interzonal transport due to a short-term source release, e.g., accidental chemical spill, in the bottom and the upper floors is predicted and corresponding HVAC system operation effects and potential responses are considered. Three-hour average exposure estimates are used to compare effects of source location and HVAC operation.

Price, P.N. "Pollutant tomography using integrated concentration data from non-intersecting optical paths." Atmospheric Environment, Volume 33, Pages 275-280. 1999. LBNL-41005.

Carrie, F.R.; Modera, M.P. "Particle Deposition in a Two Dimensional Slot from a Transverse Stream." Aerosol Science and Technology, Volume 28, Pages 235-246. 1998.

Drescher, A.C.; Park, D.Y.; Yost, M.G.; Gadgil, A.J.; Levine, S.P.; Nazaroff, W.W. "Stationary and Time-Dependent Indoor Tracer-Gas Concentration Profiles Measured by OP-FTIR Remote Sensing and SBFM Computed Tomography." Atmospheric Environment, Volume 31, Pages 727-740. 1997.

Lin, T. F.; Loy, M. D. V.; Nazaroff, W. W. "Gas-phase transport and sorption of benzene in soil." Environmental Science and Technology, Volume 30, Pages 2178-2186. 1996.

Feustel, H.E. "Annex 23 – An International Effort in Multizone Air Flow Modeling." Proceedings of the RoomVent 1996, 5th International Conference on Air Distribution in Rooms, July 17 - 19, Yokohama, Japan, Volume 2, Pages 1-8, Institute of Industrial Science, University of Tokyo, Tokyo, Japan. 1996.

Drescher, A.C.; Gadgil, A.J.; Price, P.N.; Nazaroff, W.W. "Novel Approach for Tomographic Reconstruction of Gas Concentration Distributions in Air: Use of Smooth Basis Functions and Simulated Annealing." Atmospheric Environment, Volume 30, Pages 929-940. 1996.

Faulkner, D.; Fisk, W.J.; Sullivan, D.P. "Indoor Airflow and Pollutant Removal in a Room With Floor-Based Task Ventilation: Results of Additional Experiments." Building and Environment, Volume 30, Pages 323-332. 1995. LBL-36131.

Drescher, A.C.; Lobascio, C.; Gadgil, A.J.; Nazaroff, W.W. "Mixing of a Point Source Indoor Pollutant by Forced Convection." Indoor Air, Volume 5, Pages 204-215. 1995. LBL-37895.

5. Countermeasures to Chemical and Biological Threats

Price, P.N.; Sohn, M.D.; Gadgil, A.J.; Delp, W.W.; Lorenzetti, D.M.; Finlayson, E.U.; Thatcher, T.L.; Sextro, R.G.; Derby, E.A.; Jarvis, S.A. "Protecting Buildings From a Biological or Chemical Attack: actions to take before or during a release." 2003. LBNL-51959 .

Abstract. This report presents advice on how to operate a building to reduce casualties from a biological or chemical attack, as well as potential changes to the building (e.g. the design of the ventilation system) that could make it more secure. It also documents the assumptions and reasoning behind the advice. The particular circumstances of any attack, such as the ventilation system design, building occupancy, agent type, source strength and location, and so on, may differ from the assumptions made here, in which case actions other than our recommendations may be required; we hope that by understanding the rationale behind the advice, building operators can modify it as required for their circumstances. The advice was prepared by members of the Airflow and Pollutant Transport Group, which is part of the Indoor Environment Department at the Lawrence Berkeley National Laboratory. The group's expertise in this area includes: ècents tracer-gas measurements of airflows in buildings (Sextro, Thatcher); ècents design and operation of commercial building ventilation systems (Delp); ècents modeling and analysis of airflow and tracer gas transport in large indoor spaces (Finlayson, Gadgil, Price); ècents modeling of gas releases in multi-zone buildings (Sohn, Lorenzetti, Finlayson, Sextro); ècents and occupational health and safety experience related to building design and operation (Sextro, Delp). This report is concerned only with building design and operation; it is not a how-to manual for emergency response. Many important emergency response topics are not covered here, including crowd control, medical treatment, evidence gathering, decontamination methods, and rescue gear.

Sextro, R.G.; Lorenzetti, D.M.; Sohn, M.D.; Thatcher, T.L. "Modeling the spread of anthrax in buildings." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 4, Pages 506-511, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49537 .

Abstract. The recent contamination of several U.S. buildings by letters containing anthrax demonstrates the need to understand better the transport and fate of anthrax spores within buildings. We modeled the spread of anthrax for a hypothetical office suite and estimated the distribution of mass and resulting occupant exposures. Based on our modeling assumptions, more than 90% of the anthrax released remains in the building during the first 48 hours, with the largest fraction of the mass accumulating on floor surfaces where it is subject to tracking and resuspension. Although tracking and resuspension account for only a small amount of mass transfer, the model results suggests they can have an important effect on subsequent exposures. Additional research is necessary to understand and quantify these processes.

Price, Phillip N.; Lorenzetti, D.M.; Gadgil, A. J.; Sohn, M.D.; Delp, W.W.; Jarvis, S.A. "Information for first responders to a chemical or biological attack." 2002. PUB-866.

Abstract. No Abstract available.

Price, Phillip N.; Delp, W.W.; Sohn, M.D.; Thatcher, T.L.; Lorenzetti, D.M.; Sextro, R.G.; Gadgil, A.G.; Derby, E.; Jarvis, S.A. "Advice for first responders to a building during a chemical or biological attack." 2002. PUB-867.

Abstract. No Abstract available.

Black, D.R.; Thatcher, T.L.; Delp, W.W.; Derby, E.A.; Chang, S.C.; Sextro, R.G. "Data summary report of commercial building experiments in Salt Lake City, UT from May 17 to June 10, 2002." 2002. LBNL-53801 .

Abstract. Under some circumstances, it may be desirable to provide all or part of a building with collective- protection against harmful chemical or biological (CB) agents. Collective-protection, as opposed to individual protection, uses the building – its architecture, ventilation system, and control components – to safeguard the health of the building occupants in the event of an indoor or outdoor release of toxic agents. In this study, we investigate the movement of tracer gases within a six-story

building. The building was retrofitted to provide collective-protection on the upper two floors. To achieve this protection, the upper floors were over-pressurized using outside air that had passed through military specification carbon canisters and high-efficiency particulate air (HEPA) filters. The four lower floors were outside the collective-protection area and had a ventilation system that was retrofitted to provide response modes in the event of a CB release. These response modes (e.g. building flush and shelter in place) were designed to reduce the exposure of occupants on the lower floors without compromising the collective-protection zones. Over the course of four weeks, 16 tracer gas experiments were conducted to evaluate the collective- protection system (CPS) of the building's upper two floors and the ventilation response modes of the lower floors. Tracer gas concentrations were measured at a rate of 50 Hz in up to 30 locations in each experiment, which provided data with very high spatial and temporal resolution. Differential pressure and temperature measurements were also made throughout the building. Experiments showed that the CPS maintained a positive pressure differential between the upper two floors and the lower floors with various meteorological conditions and within specified settings of the HVAC fans serving the lower floors. However, the tracer experiments did show that a CB agent could enter the first zone of the decontamination areas on each CPS floor. Tracer gas analysis also showed that the shelter in place HVAC mode provided protection of lower floor occupants from an outdoor release by significantly lowering the air exchange rates on those floors. It was also determined that the efficacy of a flush mode triggered by an agent sensor depends greatly on the location of the sensor.

Thatcher, T.L; Daisey, J.M. "Reducing mortality from urban terrorist releases of chemical and biological agents: I. Filtration for ventilation systems in commercial buildings." 2000. LBNL-44350.

Thatcher, T.L.; Sextro, R.G.; Ermak, D. "Database of Physical, Chemical, and Toxicological Properties of Chemical and Biological (CB) Warfare Agents for Modeling Airborne Dispersion In and Around Buildings." 2000. LBNL-45475 .

6. Developing Country Energy and Environmental Issues

6.1. Water Treatment

Gadgil, A.J.; Derby, E. "Providing safe drinking water to 1.1 billion unserved people." Proceedings of the 96th Annual AWMA Conference, San Diego, CA, Volume Paper No. 70492, Pages Session ES 4i, Air and Waste Management Association, Pittsburgh, PA. 2003. LBNL-52374 .

Abstract. Despite substantial advances in the past 100 years in public health, technology and medicine, 20% of the world population, mostly comprised of the poor population segments in developing countries (DCs), still does not have access to safe drinking water. To reach the United Nations (UN) Millennium Goal of halving the number of people without access to safe water by 2015, the global community will need to provide an additional one billion urban residents and 600 million rural residents with safe water within the next twelve years. This paper examines current water treatment measures and implementation methods for delivery of safe drinking water, and offers suggestions for making progress towards the goal of providing a timely and equitable solution for safe water provision. For water treatment, based on the serious limitations of boiling water and chlorination, we suggest an approach based on filtration coupled with ultraviolet (UV) disinfection, combined with public education. Additionally, owing to the capacity limitations for non-governmental organizations (NGOs) to take on this task primarily on their own, we suggest a strategy based on financially sustainable models that include the private sector as well as NGOs.

6.2. Other

Craig, P.; Gadgil, A. J.; Koomey, J. "What can history teach us?: A retrospective analysis of long-term energy forecasts for the U.S." Annual Reviews of Energy and the Environment, Volume 27, Pages 83-118. 2002. LBNL-50498 .

Abstract. This paper explores how long-term energy forecasts are created and why they are useful. It focuses on forecasts of energy use in the United States for the year 2000 but considers only long-term predictions, i.e., those covering two or more decades. The motivation is current interest in global warming forecasts, some of which run beyond a century. The basic observation is that forecasters in the 1950-1980 period underestimated the importance of unmodeled surprises. A key example is the failure to foresee the ability of the United States economy to respond to the oil embargos of the 1970s by increasing efficiency. Not only were most forecasts of that period systematically high, but forecasters systematically underestimated uncertainties. Long-term energy forecasts must make assumptions about both technologies and social systems. At their most successful, they influence how people act by showing the consequences of not acting. They are useful when they provide insights to energy planners, influence the perceptions of the public and the energy policy community, capture current understanding of underlying physical and economic principles, or highlight key emerging social or economic trends.

Gadgil, A. J.; Jannuzzi, G. M.; Silva, E.; Leonardi, M.L. "A Cost-Neutral Strategy for Maximal Use of Renewable Energy Sources and Energy Efficiency in Manaus, Brazil." Energy Policy, Volume 27, Pages 357-367. 1999. LBNL-42358.

Kazakevicius, E. "Residential Lighting in Lithuania." Energy Policy, Volume 27, Pages 603-611. 1998. LBNL-44376.

Sastry, M. A.; Gadgil, A. J. "The Bombay Efficient Lighting Large-scale Experiment (BELLE): a blueprint for improving energy efficiency and reducing peak electric demand in a developing country." Atmospheric Environment, Volume 30, Pages 803-808. 1996. LBNL-39491.

Gadgil, A. J. "Projects Toward Energy Sustainability in Cities and Rural Communities in the Developing Countries." Proceedings of the United Nations Habitat II, Istanbul. 1996.

Gadgil, A. J. "Bombay Efficient Lighting Large-Scale Experiment (Belle): Blueprint for Improving Energy Efficiency and Reducing Peak Electric Demand in a Developing Country." Atmospheric Environment, Volume 30, Pages 803-808. 1996. LBNL-39491.

Friedmann, R.; De Buen, O.; Sathaye, J.; Gadgil, A.; Saucedo, R.; Rodriquez, G. "Assessing the Residential Lighting Efficiency Opportunities in Guadalajara and Monterey, Mexico." Energy, Volume 20, Pages 151-159. 1995.

7. Environmental Tobacco Smoke

Wagner, J.; Sullivan, D.P.; Faulkner, D.; Fisk, W.J.; Alevantis, L.E.; Dod, R.L.; Gundel, L.A.; Waldman, J.M. "Environmental tobacco smoke leakage from smoking rooms." Journal of Occupational and Environmental Hygiene, Volume 1, Pages 110-118. 2004. LBNL-51010 .

Abstract. Twenty-seven laboratory experiments were conducted in a simulated smoking room to quantify rates of environmental tobacco smoke (ETS) leakage to a non-smoking area as a function of the physical and operational characteristics of the smoking room. Data are presented for the various types of leakage flows, the effect of these leaks on smoking room performance and non-smoker exposure, and the relative importance of each leakage mechanism. The results indicate that the first priority for an effective smoking room is to maintain it depressurized with respect to adjoining non-smoking areas. The amount of ETS pumped out by the smoking room door when it is opened and closed can be reduced significantly by substituting a sliding door for the standard swing-type door. An "open doorway" configuration used twice the ventilation flow as those with smoking room doors, but yielded less reduction in non-smoker exposure. Measured results correlated well with results modeled with mass-balance equations (R2 = 0.82-0.99). Most of these results are based on sulfur hexafluoride (SF6) tracer gas leakage. Because five measured ETS tracers showed good correlation with SF6, these conclusions should apply to ETS leakage as well. Field tests of a designated smoking room in an office building qualitatively agreed with model predictions.

Chan, W.R.; Price, P. N.; Gadgil, A.; Nazaroff, W.; Loosmore, G.; Sugiyama, G. "Modeling shelter-in-place including sorption on indoor surfaces." Proceedings of the 84th American Meteorological Society Annual Meeting, Seattle, WA, American Meteorological Society, Boston, MA. 2004. LBNL-53987 .

Abstract. Intentional or accidental large-scale airborne toxic releases (e.g. terrorist attacks or industrial accidents) can cause severe harm to nearby communities. As part of an emergency response plan, shelter-in-place (SIP) can be an effective response option, especially in situations when evacuation is infeasible. Reasonably tight building envelopes provide protection against exposure to peak concentrations when toxic release passes over an area. However, this protection is temporary because some toxic materials will be carried into buildings by the exchange of air between outdoors and indoors. Prompt termination of shelter-in-place after the outdoor plume has passed is also required to minimize the exposure of the occupants. The purpose of this work is to quantify the level of protection offered by existing houses, and the importance of sorption/desorption to and from surfaces on the effectiveness of SIP. We examined a hypothetical chlorine gas release scenario simulated by the National Atmospheric Release Advisory Center (NARAC). We used a standard infiltration model to calculate the distribution of time dependent infiltration rates within each census tract. Large variation in the air tightness of dwellings means some houses are more protective than others. Considering only the median air tightness, model results showed that if sheltered indoors, the total population intake of non-sorbing toxic gas is only 50% of the outdoor level 4 hours from the start of the release. Based on a sorption/desorption model by Karlsson and Huber (1996), we calculated that the sorption process would further lower the total intake of the population by an additional 50%. The potential benefit of SIP can be considerably higher if the comparison is made in terms of health effects because of the non-linear acute effect dose-response curve of many chemical warfare agents and toxic industrial substances.

Sohn, M.D.; Sextro, R.G.; Gadgil, A.J.; Daisey, J.M. "Responding to Sudden Pollutant Releases in Office Buildings: 1. Framework and Analysis Tools." Indoor Air, Volume 13, Pages 267-276. 2003. LBNL-47446 .

Abstract. We describe a framework for developing response recommendations to unexpected toxic pollutant releases in commercial buildings. It may be applied in conditions where limited building- and event-specific information is available. The framework is based on a screening-level methodology to develop insights, or rules-of-thumb, into the behavior of airflow and pollutant transport. A three-stage framework is presented: (1) develop a building taxonomy to identify generic, orprototypical, building configurations, (2) characterize uncertainty and conduct simulation modeling to predict typical airflow and pollutant transport behavior, and (3) rank uncertainty contributions to determine how information obtained at a site might reduce uncertainties in the model predictions.

The approach is applied to study a hypothetical pollutant release on the first floor of a five-story office building. Key features that affect pollutant transport are identified and described by value-ranges in the building stock. Simulation modeling provides predictions and uncertainty estimates of time-dependent pollutant concentrations, following a release, for a range of indoor and outdoor conditions. In this exercise, we predict concentrations on the fifth floor to be an order of magnitude less than on the first, coefficients of variation greater than 2, and information about the HVAC operation and window position most reducing uncertainty in predicted peak concentrations.

Klepeis, N.E.; Apte, M.G.; Gundel, L.A.; Sextro, R.G.; Nazaroff, W.W. "Determining size-specific emission factors for environmental tobacco smoke particles." Aerosol Science & Technology, Volume 37, Pages 780-790. 2003. LBNL-51049 .

Abstract. Because size is a major controlling factor for indoor airborne particle behavior, human particle exposure assessments will benefit from improved knowledge of size-specific particle emissions. We report a method of inferring size-specific mass emission factors for indoor sources that makes use of an indoor aerosol dynamics model, measured particle concentration time series data, and an optimization routine. This approach provides – in addition to estimates of the emissions size distribution and integrated emission factors – estimates of deposition rate, an enhanced understanding of particle dynamics, and information about model performance. We applied the method to size-specific environmental tobacco smoke (ETS) particle concentrations measured every minute with an 8-channel optical particle counter (PMS-LASAIR; 0.1-2+ micrometer diameters) and every 10 or 30 min with a 34-channel differential mobility particle sizer (TSI-DMPS; 0.01-1+ micrometer diameters) after a single cigarette or cigar was machine-smoked inside a low air-exchange rate 20m^3 chamber. The aerosol dynamics model provided good fits to observed concentrations when using optimized values of mass emission rate and deposition rate for each particle size range as input. Small discrepancies observed in the first 1-2 hours after smoking are likely due to the effect of particle evaporation, a process neglected by the model. Size-specific ETS particle emission factors were fit with log-normal distributions, yielding an average mass median diameter of 0.2 micrometers and an average geometric standard deviation of 2.3 with no systematic differences between cigars and cigarettes. The equivalent total particle emission rate, obtained by integrating each size distribution, was 0.2-0.7 mg/min for cigars and 0.7-0.9 mg/min for cigarettes.

Webb, A.M.; Nazaroff, W.W.; B.C. Singer. "Effect of gaseous ammonia on nicotine sorption." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 3, Pages 512-517, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-50879.

Abstract. Nicotine is a major constituent of environmental tobacco smoke. Sorptive interactions of nicotine with indoor surfaces can substantially alter indoor concentrations. The phenomenon is poorly understood, including whether sorption is fully reversible or partially irreversible. We hypothesize that acid-base chemistry on indoor surfaces might contribute to the apparent irreversibility of nicotine sorption under some circumstances. Specifically, we suggest that nicotine may become protonated on surfaces, markedly reducing its vapor pressure. If so, subsequent exposure of the surface to gaseous ammonia, a common base, could raise the surface pH, causing deprotonation and desorption of nicotine from surfaces. A series of experiments was conducted to explore the effect of ammonia on nicotine sorption to and reemission from surfaces. Our results indicate that, under some conditions, exposure to gaseous ammonia can substantially increase the rate of desorption of previously sorbed nicotine from common indoor surface materials.

Wagner, J.; Sullivan, D.P.; Faulkner, D.; Gundel, L.A.; Fisk, W.J.; Alevantis, L.E.; Waldman, J.M. "Measurements And Modeling Of Environmental Tobacco Smoke Leakage From A Simulated Smoking Room." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 2, Pages 121-126, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49785.

Abstract. The purpose of this study is to quantify the effect of various design and operating parameters on smoking room performance. Twenty-eight experiments were conducted in a simulated smoking room with a smoking machine and an automatic door opener. Measurements were made of air flows, pressures, temperatures, two particle-phase ETS tracers, two gas-phase ETS tracers,

and sulfur hexafluoride. Quantification of leakage flows, the effect of these leaks on smoking room performance and non-smoker exposure, and the relative importance of each leakage mechanism are presented. The results indicate that the first priority for an effective smoking room is to depressurize it with respect to adjoining non-smoking areas. Another important ETS leakage mechanism is the pumping action of the smoking room door. Substituting a sliding door for a standard swing-type door reduced this source of ETS leakage significantly. Measured results correlated well with model predictions (R2 = 0.82-0.99).

Singer, B.C.; Hodgson, A.T.; Nazaroff, W.W. "Effect of sorption on exposures to organic gases from environmental tobacco smoke (ETS)." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 2, Pages 138-143, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49576 .

Abstract. The effects of sorption processes on dynamic ETS organic gas concentrations and potential exposures were studied in a carpeted and furnished 50-m3 room ventilated at 0.6 h-1. Ten cigarettes were machine-smoked on six of every seven days over four weeks. Concentrations of ETS-specific tracers and regulated toxic compounds were quantified during daily smoking, post-smoking and background periods. Potential exposures were calculated by period and day. Large sorption effects were observed for the widely used tracers 3-ethenylpyridine and nicotine, and for several toxic compounds including naphthalene and cresol isomers. Short-term adsorption to indoor surfaces reduced concentrations and potential exposures during smoking, while later reemission increased concentrations and exposures hours after smoking ended. Concentrations during nonsmoking periods rose from day to day over the first few weeks, presumably from increased reemission associated with increased sorbed mass concentrations. For sorbing compounds, more than half of daily potential exposures occurred during nonsmoking periods.

Nazaroff, W.W.; B.C. Singer. "Inhalation of hazardous air pollutants from environmental tobacco smoke in US residences." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 2, Pages 477-482, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-50878 .

Abstract. In the United States, 48 million adults smoke 5 x 10^11 cigarettes per year. Many cigarettes are smoked in private residences causing regular environmental tobacco smoke (ETS) exposure to at least 31 million nonsmokers (11% of the US population), including 16 million juveniles. ETS contains many chemical species whose industrial emissions are regulated by the US federal government as hazardous air pollutants (HAPs). In this paper, average daily residential exposures to 15 HAPs in ETS are estimated for US nonsmokers who live with smokers. The evaluation is based on material-balance modeling, and utilizes published data on smoking habits, demographics, and housing. Newly measured exposure-relevant emission factors are incorporated. Comparison of exposure concentration estimates with health-based guidelines for chronic exposure suggests that aldehydes – specifically acrolein, acetaldehyde, and formaldehyde – should be of particular concern in ETS. Cumulative population intake results are compared for these compounds against other sources of exposure.

Klepeis, N.E.; W.W. Nazaroff. "Characterizing size-specific ETS particle emissions." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 2, Pages 162-167, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-50938.

Abstract. We report a method for estimating the size distribution of particle emissions from indoor sources. The method is applied to concentration data from a series of cigar and cigarette experiments to characterize environmental tobacco smoke particles. The method incorporates a particle dynamics model, which provided good fits to observed concentrations when using, as input, optimal values of mass emission rate and deposition velocity for each particle size range. The optimal particle emissions were fit to log-normal distributions, yielding mass median diameters of approximately 0.2 ?m and an average geometric standard deviation of 2.3. The total particle emissions obtained by integrating the empirical size distribution were 0.2 – 0.7 mg/min for cigars and 0.7 – 0.9 mg/min for cigarettes. The measurements of particle size characteristics agree well with prior research, but the integrated mass measurements are consistently lower than those determined from filter-based measurements.

Apte, M.G.; Gundel, L.A.; Dod, R.; Chang, G.M.; Sextro, R. G. "A pilot study of the behavior of gas- and particle-phase ETS tracers in residences." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 2, Pages 500-505, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49585 .

Abstract. Our previous study of environmental tobacco smoke (ETS) in a three-room environmental chamber showed that smoking history significantly influenced inter-room ETS transport , particularly of gas-phase nicotine. We conducted a three-home pilot study where smoking was limited to one room. Single-smoker residences were monitored during five one-week periods while the smoker participated in a smoking cessation program. Nicotine traced ETS particles were detected reliably in the smoking rooms (SRs) and unreliably in the non-smoking rooms (NSRs). On average, the ventilation- and volume-normalized smoking rate, 0.1 Cigarette-h-1m-3, added about 17 and 4 ?g m-3of ETS particles into the SR and NSR, while average nicotine concentration increases were 2 and 0.06 ?g m-3, respectively. Thus, nicotine tracers may underestimate ETS particle exposure in a NSR (e.g., a child's bedroom) by a factor of 2 to 8. In other words, ETS exposure predicted from nicotine concentrations could be almost an order of magnitude lower than actual exposure.

Klepeis, N.E.; Apte, M G.; Gundel, L A.; Nazaroff, W.W.; Sextro. R G. "Characterizing ETS Emissions from Cigars: Chamber Measurements of Nicotine, Particle Mass, and Particle Size." Proceedings of the Indoor Air '99 Conference, Edinburgh, Scotland, Volume 2, Pages 903-908, Construction Research Communications, Ltd., London. 1999. LBNL-43840.

Apte, M.G.; Gundel, L.A.; Singer, B.C.; Sullivan, D.P.; Sextro, R.G. "Indoor Transport of ETS Particles And Tracers." Proceedings of the Indoor Air '99 Conference, Edinburgh, Scotland, Volume 2, Pages 965-970, Construction Research Communications, Ltd., London. 1999. LBNL-43841.

Van Loy, M. D.; Nazaroff, W. W.; Daisey, J. M. "Nicotine as a Marker for Environmental Tobacco Smoke: Implications of Sorption on Indoor Surface Materials." Journal of Air and Waste Management Association, Volume 48, Pages 959-968. 1998. LBNL-42363.

Van Loy, M. D.; Lee, V. C.; Gundel, L. A.; Daisey, J. M.; Sextro, R. G.; Nazaroff, W. W. "Dynamic behavior of semi-volatile organic compounds in indoor air: 1. Nicotine in a stainless steel chamber." Environmental Science and Technology, Volume 31, Pages 2554-2561. 1997. LBNL-42674.

Van Loy, M. D.; Nazaroff, W. W.; Daisey, J. M. "Sorptive interactions of gas-phase environmental tobacco smoke components with carpet, Paper No. 97-MP3.05." Proceedings of the Air & Waste Management Association's 90th Annual Meeting & Exhibition, Toronto, Ontario, Canada, Air and Waste Management Association, Pittsburgh, PA. 1997.

Gundel, L.A.; Hansen, A.D.A. "Real-time measurement of environmental tobacco smoke by ultraviolet absorption." Proceedings of the Sixteenth Annual Conference of the American Association for Aerosol Research, October 13-17, 1997, Denver, CO, Pages 419, American Association for Aerosol Research, Cincinnati, OH. 1997.

Daisey, J. M.; Mahanama, K. R. R.; Hodgson, A. T. "Toxic volatile organic compounds in simulated environmental tobacco smoke: Emission factors for exposure assessment." Exposure Analysis and Environmental Epidemiology, Volume 8, Pages 313-334. 1997.

Daisey, J. M.; Nazaroff, W. W. "Implications of nicotine sorption on indoor surfaces on its use as a marker for environmental tobacco smoke." Proceedings of the A&WMA/EPA Symposium: Engineering Solutions to IAQ Problems, Research Triangle Park, NC, Air and Waste Management Association, Pittsburgh, PA. 1997.

Van Loy, M. D.; Nazaroff, W. W.; Lee, V. C.; Gundel, L. A.; Sextro, R. G.; Daisey, J. M. "Investigation of the fate of nicotine in a stainless-steel chamber." Proceedings of the 89th Annual Meeting of the Air and Waste Management Association, Nashville, TN, Air and Management Association, Pittsburgh, PA. 1996.

Mahanama, K. R. R.; Daisey, J. M. "Volatile N-nitrosamines in Environmental Tobacco Smoke: Sampling, Analysis, Emission Factors and Indoor Air Exposures." Environmental Science and Technology, Volume 30, Pages 1477-1484. 1996.

Wampler, D. A.; Miller-Leiden, S.; Nazaroff, W. W.; Litvak, A.; Mahanama, K. R. R.; Nematollahi, A.; Gadgil, A. J. "Effectiveness of Smokeless Ashtrays." Journal of Air and Waste Management Association, Volume 45, Pages 494-500. 1995. LBNL-39492.

Hodgson, A.T.; Daisey, J.M.; Alevantis, L.E.; Mahanama, K.R.R.; Ten Brinke, J. "Use of Volatile Tracers to Determine the Contribution of Environmental Tobacco Smoke to Concentrations of Volatile Organic Compounds in Smoking Environments." Environmental International, Volume 22, Pages 295-307. 1995. LBL-37376.

8. Exposure and Risk Assessment

Lobscheid, A.B.; McKone, T.E. "Constraining uncertainties about the sources and magnitude of polycyclic aromatic hydrocarbon (PAH)levels in ambient air: the State of Minnesota as a case study." To be submitted to Journal of Atmospheric Environment. 2004. LBNL-54473 .

Abstract. Emissions data are often lacking or uncertain for many airborne contaminants. Chemicals, such as polycyclic aromatic hydrocarbons (PAHs), emitted from combustion sources, fall into this category. Currently available ambient-air emission inventories of PAHs either fail to account for population-based activities (such as residential wood combustion and motor vehicle activity) and/or report 'total PAH' or particulate organic matter emissions instead of individual compounds. We measure the degree of overlap between predicted concentrations from estimated emissions with measured concentrations. Our analysis is, based on probabilistic analysis of measured outdoor air concentrations with those predicted from mass-balance models. . Based on available information, we estimate the relative magnitude of emissions from four major sources of PAHs to outdoor air- (1) on-road motor vehicles, including light-duty gasoline vehicles and diesel-powered buses and medium and heavy duty trucks; (2) residential wood combustion; and (3) power generation from external combustion boilers. We use the CalTOX regional multimedia mass-balance model to evaluate our emissions estimates in rural and urban regions of the state of Minnesota, USA. We compare model estimates of outdoor PAH airborne concentrations with those reported by the Minnesota Children's Pesticide Exposure Study (MNCPES). With these measured concentrations we probabilistically evaluate our emissions and interpret the reliability of our emissions estimates for specific PAHs. The median estimates of our predicted outdoor air concentrations agree within an order of magnitude of measured concentrations. For four representative PAHs, we were able to obtain a reasonable degree of overlap between empirical and predicted distributions of outdoor air concentrations. Our combination of models, emissions estimates, and empirical concentration data estimate exposure in a manner that is more reliable than any of these tools alone. Thereby, we increase our confidence about our plausible ranges of emissions and predicted concentrations

Marshall, J. "Exposure to Motor Vehicle Emissions: An Intake Fraction Approach, Master's Thesis." 2002. LBNL-51854 .

Abstract. Motor vehicles are a significant source of population exposure to air pollution. Focusing on California's South Coast Air Basin as a case study, I combine ambient monitoring station data with hourly time-activity patterns to determine the population intake of motor vehicle emissions during 1996 – 1999. Three microenvironments are considered wherein the exposure to motor vehicle emissions is higher than in ambient air: in and near vehicles, inside a building that is near a freeway, and inside a residence with an attached garage. Total motor vehicle emissions are taken from the EMFAC model. The 15 million people in the South Coast inhale 0.0048% of primary, nonreactive compounds emitted into the basin by motor vehicles. Intake of motor vehicle emissions is 46% higher than the average ambient concentration times the average breathing rate, because of microenvironments and because of temporal and spatial correlation among breathing rates, concentrations, and population densities. Intake fraction (iF) summarizes the emissions-to-intake relationship as the ratio of population intake to total emissions. iF is a population level exposure metric that incorporates spatial, temporal, and interindividual variability in exposures. iFs can facilitate the calculation of population exposures by distilling complex emissions-transport-receptor relationships. I demonstrate this point by predicting the population intake of various primary gaseous emissions from motor vehicles, based on the intake fraction for benzene and carbon monoxide.

Lorenzetti, D.M. "Predicting Indoor Pollutant Concentrations, and Applications to Air Quality Management." Proceedings of the Joint WHO-JRC-ECA Workshop on the Role of Human Exposure Assessment in Air Quality Management, Bonn, Germany. 2002. LBNL-51582 .

Abstract. Because most people spend more than 90% of their time indoors, predicting exposure to airborne pollutants requires models that incorporate the effect of buildings. Buildings affect the exposure of their occupants in a number of ways, both by design (for example, filters in ventilation systems remove particles) and incidentally (for example, sorption on walls can reduce peak

concentrations, but prolong exposure to semivolatile organic compounds). Furthermore, building materials and occupant activities can generate pollutants. This paper surveys modeling approaches for predicting pollutant concentrations in buildings, and summarizes the application of these models.

Sohn, Michael D.; Thomas E. McKone; Mark L. Rigas; Jerry N. Blancato; Frederick W. Power. "Reconstructing exposure scenarios using dose biomarkers: An application of Bayesian uncertainty analysis." 2001. LBNL-51256.

8.1. Exposure and Health Effects

Sohn, M.D.; TE McKone; JN Blancato. "Reconstructing Population Exposures from Dose Biomarkers: Inhalation of Trichloroethylene (TCE) as a Case Study." Journal of Exposure Analysis and Environmental Epidemiology, Volume 14, Pages 204-213. 2004. LBNL-50588 .

Abstract. Physiologically based pharmacokinetic (PBPK) modeling is a well-established toxicological tool designed to relate exposure to a target tissue dose. The emergence of federal and state programs for environmental health tracking and the availability of exposure monitoring through biomarkers creates the opportunity to apply PBPK models to estimate exposures to environmental contaminants from urine, blood, and tissue samples. However, reconstructing exposures for large populations is complicated by often having too few biomarker samples, large uncertainties about exposures, and large inter-individual variability. In this paper we use an illustrative case study to identify some of these difficulties and for a process for confronting them by reconstructing population-scale exposures using Bayesian inference. The application consists of interpreting biomarker data from eight adult males with controlled exposures to trichloroethylene (TCE) as if the biomarkers were random samples from a large population with unknown exposure conditions. The TCE concentrations in blood from the individuals fell into two distinctly different groups even though the individuals were simultaneously in a single exposure chamber. We successfully reconstructed the exposure scenarios for both subgroups – although the reconstruction of one subgroup is different than what is believed to be the true experimental conditions. We were however unable to predict with high certainty the concentration of TCE in air.

Russell, M.; Goth-Goldstein, R.; Apte, M G.; Fisk, W.J. "Methods to determine the size distribution of airborne rhinovirus." Accepted for publication in Indoor Air. 2004. LBNL-54916.

Abstract. About 50% of viral-induced respiratory illnesses are caused by the human rhinovirus (HRV). Prior research has demonstrated that rhinovirus infections can be transmitted via person-to-person contact and via inhalation of infectious aerosols. Measurements of the concentrations and sizes of bioaerosols are critical for research on building characteristics, aerosol transport, and mitigation measures. To detect airborne HRV, we developed a quantitative reverse transcription-coupled polymerase chain reaction (RT-PCR) assay and verified that this assay detects HRV in nasal lavage samples. A quantitation standard was used to determine the assay detection limit of 5 fg of HRV RNA with a linear range over 10,000-fold. This assay was used to quantify the size distribution of an artificially-produced HRV aerosol captured with an Andersen six-stage cascade impactor. In future studies, we hope to use the methods developed here to characterize the size distribution of naturally occurring viral-aerosols.

MacLeod, Matthew. "Overall multi-media persistence as an indicator of potential for population-level intake of environmental contaminants." Accepted for publication in Environmental Toxicology and Chemistry. 2004. LBNL-53245 .

Abstract. Although it is intuitively apparent that population-level exposure to contaminants dispersed in the environment must related to the persistence of the contaminant, there has been little effort to formally quantify this link. In this paper we investigate the relationship between overall persistence in a multimedia environment and the population-level exposure as expressed by intake fraction (iF), which is the cumulative fraction of chemical emitted to the environment that is taken up by members of the population. We first confirm that for any given chemical contaminant and emission scenario the definition of iF implies that it is directly proportional to the overall multi-media

persistence, POV. We show that the proportionality constant has dimensions of time and represents the characteristic time for population intake (CTI) of the chemical from the environment. We then apply the CalTOX fate and exposure model to explore how POV and CTI combine to determine the magnitude of iF. We find that CTI has a narrow range of possible values relative to POV across multiple chemicals and emissions scenarios. We use data from the Canadian Environmental Protection Act Priority Substance List (PSL1) Assessments to show that exposure assessments based on empirical observation are consistent with interpretations from the model. The characteristic time for intake along different dominant exposure pathways is discussed. Results indicate that POV derived from screening-level assessments of persistence, bioaccumulation potential, and toxicity (PBT) is a useful indicator of the potential for population-level exposure.

MacLeod, M.J.; Bennet, D.H.; Perem, M.; Maddalena, R.L.; McKone, T.E.; Mackay, D. "Dependence of intake fraction on release location in a multi-media framework: A case study of four contaminants in North America." Accepted for publication in Journal of Industrial Ecology. 2004. LBNL-52369 .

Abstract. The extent of human exposure to persistent anthropogenic environmental contaminants is a complex function of the amount of chemical emitted, its physico-chemical properties and reactivity, the nature of the environment, and the characteristics of the pathways for human exposure, such as inhalation, intake of food and water and dermal contact. For some chemicals, the location of emissions relative to areas of high population density or intense food production may also be an important factor. The relative importance of these variables is explored using the regionally segmented BETR North America contaminant fate model and data for food production patterns and population density for North America. The model is applied to four contaminants emitted to air: benzene, carbon tetrachloride, benzo[a]pyrene and 2,3,7,8- tetrachlorodibenzo dioxin. The total continental intake fraction (iF), relating exposure quantity to emission quantity, is employed as a metric for assessing population exposure to environmental contaminants. The results show that the use of continentally averaged parameters for population density and food production provides an accurate estimate of the median of iF calculated for emissions in individual regions, however iF can range from this median by up to 3 orders of magnitude, especially for chemicals transferred to humans through the food pathway. The location of population relative to food production and emissions of chemicals are important variables that should be considered in assessing the public health implications of chemical emissions.

Maddalena, R.L.; McKone, T.E.; Sohn, M.D. "Standardized Approach for Developing Probabilistic Exposure Factor Distributions." Submitted to Risk Analysis. 2003. LBNL-52203 .

Abstract. The effectiveness of a probabilistic risk assessment (PRA) depends critically on the quality of input information that is available to the risk assessor and specifically on the probabilistic exposure factor distributions that are developed and used in the exposure and risk models. Deriving probabilistic distributions for model inputs can be time consuming and subjective. The absence of a standard approach for developing these distributions can result in PRAs that are inconsistent and difficult to review by regulatory agencies. We present an approach that reduces subjectivity in the distribution development process without limiting the flexibility needed to prepare relevant PRAs. The approach requires two steps. First, we analyze data pooled at a population scale to (i) identify the most robust demographic variables within the population for a given exposure factor, (ii) partition the population data into subsets based on these variables, and (iii) construct archetypal distributions for each subpopulation. Second, we sample from these archetypal distributions according to site- or scenario-specific conditions to simulate exposure factor values and use these values to construct the scenario-specific input distribution. It is envisaged that the archetypal distributions from step 1 will be generally applicable so risk assessors will not have to repeatedly collect and analyze raw data for each new assessment. We demonstrate the approach for two commonly used exposure factors – body weight (BW) and exposure duration (ED) – using data for the U.S. population. For these factors we provide a first set of subpopulation based archetypal distributions along with methodology for using these distributions to construct relevant scenario-specific probabilistic exposure factor distributions.

Maddalena, R.L.; McKone, T.E. "Is there a "forest filter effect" for organic pollutants?." Stochastic Environmental Research and Risk Assessment, Volume 17, Pages 231-234. 2003. LBNL-51882 .

Abstract. No abstract available

MacLeod, M.J. "On the influence of forests on the overall fate of semivolatile organic contaminants." Stochastic Environmental Research and Risk Assessment, Volume 17, Pages 256-259. 2003. LBNL-52156 .

Abstract. Convincing experimental evidence exists that the presence of vegetation, especially forest canopies, enhances scavenging of semi-volatile organic chemicals (SVOCs) from the atmosphere and increases their depositional flux to the terrestrial surface relative to deposition to bare soil. Evidence from several modeling studies indicates that gaseous deposition to vegetation is the most efficient scavenging pathway, and, due to interactions between gas-particle partitioning in the atmosphere and resistance to diffusion through the cuticle of plants, that pathway is available for SVOCs with Log Koa between 7 and 11 and Log Kaw ¿ -6. However, for enhanced scavenging by vegetation to influence the overall regional and global fate of SVOCs, it must represent a process that is competitive with the other fate and transport processes in the ecological system under consideration. The key question in evaluating the importance of the "Forest Filter Effect" on the regional and global fate of SVOCs is: Does scavenging from the atmosphere by vegetation have a significant influence on the inter-media partitioning, long-range transport and/or environmental persistence of SVOCs? Based on evidence presented below from the CoZMo-POP model and supported by results from other models that together represent our current state of knowledge, the Forest Filter Effect does not exert a controlling influence over regional or global contaminant fate and transport.

Erdmann, C.A.; Satariano, W.A.; Chen, Y.Q. "Traditional risk factor study (TRiFS): Preliminary report on risk factor prevalence and population attributable fraction estimates for breast cancer in Marin County, California." 2003. LBNL-51905 .

Abstract. The objective of the Traditional Risk Factor Study (TRiFS) was to describe female breast cancer risk factor distributions in Marin County, California by using previously collected, individual-level data. The Marin County breast cancer risk factor distributions were compared with those of the other California counties and the State. Prevalence estimates for traditional breast cancer risk factors (e.g., age at menarche, family history, and age at first birth) were computed using data from the Marin County Breast Cancer Study of Adolescent Risk Factors (ARFS) and the California Health Interview Survey (CHIS). A reference set of relative risk values for the breast cancer risk factors of interest was assembled from published sources. Using the prevalence estimates along with these relative risk values, population attributable fractions were calculated for selected breast cancer risk factors and combinations of these factors. Approximately 84% of Marin County women were exposed to at least one of the following five breast cancer risk factors: earlier age at menarche, later age at 1st birth or nulliparity family history, later age at menopause, and/or higher postmenopausal body mass index (BMI). The results suggest that 50% of Marin County's breast cancer cases would be avoided if the traditional breast cancer risk factors considered in these analyses were eliminated. Later age at first birth and nulliparity after age 30 alone appear to account for about one-third of breast cancer cases in Marin County.

Erdmann, C.A.; Farren, G.; Baltzell, K.; Chew, T.; Clarkson, C.; Fleshman, R.; Leary, C.; Mizroch, M.; Orenstein, F.; Russell, ML.; Souders-Mason, V.; Wrensch, M. "Breast Cancer and Personal Environmental Risk Factors in Marin County – Pilot Study." 2003. LBNL-52484 .

Abstract. The purpose of the Personal Environmental Risk Factor Study (PERFS) pilot project was to develop methodologies and a questionnaire for a future population-based case-control study to investigate the role of selected environmental exposures in breast cancer development. Identification of etiologically relevant exposures during a period of potential vulnerability proximate to disease onset offers the possibility of clinical disease prevention even when disease initiation may have already occurred many years earlier. Certain personal environmental agents or combinations of agents may influence disease promotion. Therefore, this pilot study focused on exposures that occurred during the ten-year period prior to diagnosis for cases and the last ten years for controls, rather than more historic exposures. For this pilot study, we used a community-based research approach. In our

collaborative efforts, community members participated with academic researchers in all phases of the research, including research question identification, study design, development of research tools, development of the human subjects protocol, and report writing. Community member inclusion was based upon the concept that community participation could improve the relevance of scientific studies and ultimate success of the research by encouraging an ongoing dialogue between community members and academic representatives. Early activities of this project focused on the collection of input from the community regarding the possible role of environmental factors in the incidence of breast cancer in Marin County. The intent was to inform the scientists of community concerns, enhance the research team's understanding of the community being studied, and provide interested community members with a better understanding of the strengths and weaknesses of traditional research methods through active participation in the research process. This pilot study identified specific testable hypotheses through review of the literature and consultation with relevant experts and the affected community. Initially, the study was to focus on modifiable personal environmental exposures that are associated with breast tumor promotion and higher socioeconomic status (SES). However, little information was available in the scientific literature regarding the putative mechanism by which some of the suspected environmental factors may act (i.e., initiator vs. promoter). Likewise, little is known about the distribution of personal environmental risk factors by socioeconomic status. Therefore, tumor promotion involvement and association with SES were not very useful as selection criteria, and selection of topics was based primarily on published scientific findings of human studies and community input. This study was approved by the Institutional Review Boards at the University of California at San Francisco (Committee on Human Research) and at the University of California at Berkeley (Committee for the Protection of Human Subjects).

Russell, M.L.; Goth-Goldstein, R.; Apte, M.G.; Fisk, W.J. "Method for measuring the size distribution of airborne rhinovirus." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 40-45, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49574.

Abstract. About 50% of viral-induced respiratory illnesses are caused by the human rhinovirus (HRV). Measurements of the concentrations and sizes of bioaerosols are critical for research on building characteristics, aerosol transport, and mitigation measures. We developed a quantitative reverse transcription-coupled polymerase chain reaction (RT-PCR) assay for HRV and verified that this assay detects HRV in nasal lavage samples. A quantitation standard was used to determine a detection limit of 5 fg of HRV RNA with a linear range over 1000-fold. To measure the size distribution of HRV aerosols, volunteers with a head cold spent two hours in a ventilated research chamber. Airborne particles from the chamber were collected using an Andersen Six-Stage Cascade Impactor. Each stage of the impactor was analyzed by quantitative RT-PCR for HRV. For the first two volunteers with confirmed HRV infection, but with mild symptoms, we were unable to detect HRV on any stage of the impactor.

Pang, Y.; Gundel, L.A.; Larson, T.; Finn, D.; Liu, L.J. Sally; Claiborn, C.S. "Development and evaluation of a personal particulate organic and mass sampler." Environmental Science and Technology, Volume 36, Pages 5205-5210. 2002. LBNL-50850 .

Abstract. Accurate measurement of personal exposure to particulate matter and its constituents requires samplers that are accurate, compact, lightweight, inexpensive and convenient to use. The Personal Particulate Organic and Mass Sampler (PPOMS) has been developed to meet these criteria. The PPOMS uses activated carbon- impregnated foam as a combined 2.5-?m size-selective inlet and denuder for assessment of fine particle mass and organic carbon. Proof of the PPOMS concept has been established by comparing mass and organic carbon in particles collected with collocated samplers in Seattle, at a central outdoor site and in residences. Daily particulate mass concentrations averaged 10.0?5.2, 12.0?5.3, and 11.2?5.1 ?g m-3 for the Federal Reference Method, the Harvard Personal Exposure Monitor, and the PPOMS, respectively, for 10 24-h sampling periods. During a series of PM2.5 indoor organic carbon (OC) measurements from single quartz filters, the apparent indoor OC averaged 7.7?0.8 ?g of C m-3, which was close to the indoor PM2.5 mass from collocated Teflon filters (7.3?2.3 ?g of C m-3), indicating the presence of a large positive OC artifact. In collocated measurements, the PPOMS eliminated this artifact just as well as the Integrated Gas

and Particle Sampler that incorporated a macroreticular poly(styrene- divinylbenzene) (XAD-4) resin- coated denuder, yielding OC concentrations of 2.5 ? 0.4 and 2.4 ? 1.0 ?g C m-3, respectively. Thermal analysis for OC indicated that the indoor positive artifact was due to adsorption of gas-phase SVOC. This study shows that the PPOMS design provides a 2.5-?m size-selective inlet that also prevents the adsorption of gas-phase semi-volatile organic compounds onto quartz filters, thus eliminating the filter positive artifact. The PPOMS meets a significant current challenge for indoor and personal sampling of particulate organic carbon. The PPOMS design can also simplify accurate ambient sampling for PM2.5.

Holman, H.Y.; Goth-Goldstein, R.; Aston, D.; Mao, Y.; Kengsoontra, J. "Evaluation of gastrointestinal solubilization of petroleum hydrocarbon residues in soil using an in vitro physiologically- based model." Environmental Science & Technology, Volume 36, Pages 1281-1286. 2002. LBNL-48401.

Abstract. No Abstract available

Goth-Goldstein, R.; Russell, M.L.; Parimoo, B.; Weyand, E.H. "7H-Benzo[c]fluorene DNA adduct formation in different human cells in culture." 2002. LBNL-50479.

Abstract. 7H-Benzo[c]fluorene (B[c]F) has been known for a long time as a component of complex mixtures such as coal tar or cigarette smoke. B[c]F has been identified recently as a potent lung tumorigen and a major DNA adduct-forming component of coal tar. We have investigated if human cells have the ability to form B[c]F:DNA adducts as detected in lungs of mice treated with B[c]F. MCF7 (human breast cancer), HepG2 (hepatoma) and Caco-2 (colon adenocarcinoma) cells were treated with increasing concentrations (0.2 – 10 *g/ml) of B[c]F for 20 hours. Adduct formation was evaluated using 32P-postlabeling. A dose response in DNA adduct formation was detected in all three cell lines. In MCF7 and HepG2 cells, two adducts were detected, one of them corresponded to an adduct observed in the lungs of mice treated with B[c]F. This adduct is derived from 3-hydroxy B[c]F while the second, slower migrating adduct, appears to be unique to human cells. In contrast, Caco-2 cells formed at least four adducts. Two of the three most predominant adducts correspond to the two adducts observed in MCF7 and HepG2 cells while the additional predominate and a minor adduct are derived from 3,4-dihydrodiol B[c]F. The adducts derived from 3,4- dihydrodiol B[c]F are similar to those observed in mouse lung and skin. The detection of B[c]F:DNA adducts clearly demonstrates that human cells have the capacity to metabolically activate B[c]F to derivatives that covalently modify DNA. Similarities in the types of B[c]F:DNA adducts detected also demonstrates that B[c]F activation is similar in both human cells and mouse tissue.

Fischer, M.; Littlejohn D.; Lunden, M.; Gundel, L.A.; Dod, R.; Brown N.J. "An instrument for automated simultaneous measurements of ammonia and nitric acid in indoor and outdoor air." 2002. LBNL-51005.

Abstract. No Abstract available.

De Martinis, B.S.; Okamoto, R.A.; Kado, N.Y.; Gundel, L.A.; Carvalho, L.R.F. "Polycyclic aromatic hydrocarbons in a bioassay-directed fractionated extract of PM10 collected in Sao Paulo, Brazil." Atmospheric Environment, Volume 36, Pages 307-314. 2002. LBNL-48453 .

Abstract. No Abstract available

Castorina, R.; Bradman, A.; McKone, T.E. "Assessing cumulative organophosphate pesticide exposure and risk among pregnant women living in an agricultural community." Environmental Health Perspectives, Volume 111, Pages 1640-1648. 2002. LBNL-51334 .

Abstract. Approximately 225,000 kilograms of organophosphate (OP) pesticides are used annually in California's Salinas Valley, which is intensively farmed for vegetables and fruit. These activities have raised concerns about pesticide exposures to area residents. As part of a prospective cohort study, we collected three spot urine samples from 462 pregnant women and analyzed them for six dialkyl phosphate metabolites. Based on these urinary metabolite concentrations, we estimated OP pesticide doses with deterministic steady-state models using two methods: the first method assumed the pesticide metabolites were attributable entirely to a single diethyl or dimethyl OP pesticide; the second method adapted U.S. EPA draft guidelines for cumulative risk assessment to

estimate dose from a mixture of OP pesticides that share a common mechanism of toxicity. We used pesticide use reporting data for the Salinas Valley to quantify the likely mixture to which the women were exposed. Based on average OP pesticide dose estimates that assumed exposure to a single OP pesticide (Method 1), between 0% and 36.0% of study participants' exposures exceeded the U.S. EPA oral benchmark dose10 (BMD10) divided by a 100-fold uncertainty factor, depending on the assumption made about the parent compound. These BMD10 values were derived from studies of brain cholinesterase inhibition in rats. 14.7% of the participants' average cumulative OP pesticide dose estimates (Method 2) exceeded the BMD10 of the selected index chemical divided by a 100- fold uncertainty factor, regardless of index chemical chosen. An uncertainty analysis of the pesticide mixture parameter suggests that this point estimate could range from 1%-38%. Because our reference value (BMD10/100) may not account for the special sensitivity of the developing fetus, this research points to the need for modeling approaches to estimate fetal exposures and assess risk from prenatal OP pesticide exposure.

Bodnar, A.B.; Maddalena, R.L.; McKone, T.E. "Addressing locally grown foods in cumulative exposure assessments." Journal of Exposure Analysis and Environmental Epidemiology, Volume 14, Pages 60-73. 2002. LBNL-50378 .

Abstract. Both laboratory and field studies confirm the importance of vegetation for scavenging semi-volatile organic chemicals (SVOCs) from the atmosphere and a number of exposure studies have found that the dietary pathway is often a significant contributor to cumulative exposure for these chemicals. Exposure calculations based on published concentration data for foods indicate that the potential intake through ingestion is up to 1000 times that of inhalation for several persistent SVOCs. However, little information exists on the source-to-dietary intake linkage for SVOC's. Because of higher SVOC emissions to urban regions, this linkage is particularly important for foods that are grown, distributed and consumed in or near urban regions. The food pathway can also contribute to dietary exposure for populations that are remote from a pollutant source if the pollutants can migrate to agricultural regions and subsequently to the agricultural commodities distributed to that population. We use the characteristic travel distance (CTD) and available data within the CalTOX multimedia model framework to assess the contribution of local food markets to the fraction of cumulative food intake that is attributable to local sources. For a set of three representative multimedia SVOCs- benzo(a)pyrene, fluoranthene, and 2,3,7,8-TCDD, we explore the contribution of airborne SVOC's to cumulative uptake through the local food consumption pathway. We use the population based intake fraction (iF) to determine how SVOC intake varies among food commodities and compares to inhalation. The approach presented here provides a useful framework and starting point for source-to-intake assessments for the air-to-dietary exposure pathway.

Bennett, D.H.; Furtaw, E.J.; McKone, T.E. "A fugacity-based indoor residential pesticide fate model." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 261-266, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-53458 .

Abstract. Dermal and non-dietary pathways are potentially significant exposure pathways to pesticides used in residences. Exposure pathways include dermal contact with residues on surfaces, ingestion from hand- and object-to-mouth activities, and absorption of pesticides into food. A limited amount of data has been collected on pesticide concentrations in various residential compartments following an application. But models are needed to interpret this data and make predictions about other pesticides based on chemical properties. In this paper, we propose a mass-balance compartment model based on fugacity principles. We include air (both gas phase and aerosols), carpet, smooth flooring, and walls as model compartments. Pesticide concentrations on furniture and toys, and in food, are being added to the model as data becomes available. We determine the compartmental fugacity capacity and mass transfer-rate coefficient for wallboard as an example. We also present the framework and equations needed for a dynamic mass- balance model.

McKone, T.E.; E.G. Hertwich. "The Human Toxicity Potential and a Strategy for Evaluating Model Performance in Life-Cycle Impact Assessment." International Journal of Life-Cycle Assessment, Volume 6, Pages 106-109. 2001. LBNL-48254 .

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McKone, T.E.; Hammond, S.K. "Managing the health impacts of waste incineration." Environmental Science & Technology, Volume 34, Pages 380A-387A. 2000. LBNL-46084 .

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8.2. Pollutant Fate and Transport Modeling

Toose, L.; Woodfine, D.G.; MacLeod, M.; Mackay, D.; Gouin, J. "BETR-World: A geographically explicit model of chemical fate - application to transport of a-HCH to the Artic." Environmental Pollution, Volume 128, Pages 223-240. 2004. LBNL-54148 .

Abstract. The BerkeleyTrent (BETR)-World model, a 25 compartment, geographically explicit fugacity-based model is described and applied to evaluate the transport of chemicals from temperate source regions to receptor regions (such as the Arctic). The model was parameterized using GIS and an array of digital data on weather, oceans, freshwater, vegetation and geo-political boundaries. This version of the BETR model framework includes modi.cation of atmospheric degradation rates by seasonally variable hydroxyl radical concentrations and temperature. Degradation rates in all other compartments vary with seasonally changing temperature. Deposition to the deep ocean has been included as a loss mechanism. A case study was undertaken for a-HCH. Dynamic emission scenarios were estimated for each of the 25 regions. Predicted environmental concentrations showed good agreement with measured values for the northern regions in air, and fresh and oceanic water and with the results from a previous model of global chemical fate. Potential for long-range transport and deposition to the Arctic region was assessed using a Transfer Efficiency combined with estimated emissions. European regions and the Orient including China have a high potential to contribute a-HCH contamination in the Arctic due to high rates of emission in these regions despite low Transfer Efficiencies. Sensitivity analyses reveal that the performance and reliability of the model is strongly in.uenced by parameters controlling degradation rates.

Prevedouros, K.; MacLeod, M.; Jones, K.C.; Sweetman, A.J. "Modelling the fate of persistent organic pollutants in Europe: Parameterisation of a gridded distribution model." Environmental Pollution, Volume 128, Pages 251-261. 2004. LBNL-54147 .

Abstract. A regionally segmented multimedia fate model for the European continent is described together with an illustrative steady-state case study examining the fate of g-HCH (lindane) based on 1998 emission data. The study builds on the regionally segmented BETR North America model structure and describes the regional segmentation and parameterisation for Europe. The European continent is described by a 5 degrees x 5 degrees grid, leading to 50 regions together with four perimetric boxes representing regions bufferring the European environment. Each zone comprises seven compartments including; upper and lower atmosphere, soil, vegetation, fresh water and sediment and coastal water. Inter-regions flows of air and water are described, exploiting information originating from GISdatabases and other georeferenced data. The model is primarily designed to describe the fate of Persistent Organic Pollutants (POPs) within the European environment by examining chemical partitioning and degradation in each region, and inter-region transport either under steady-state conditions or fully dynamically. A test case scenario is presented which examines the fate of estimated spatially resolved atmospheric emissions of lindane throughout Europe within the lower atmosphere and surface soil compartments. In accordance with the predominant wind direction in Europe, the model predicts high concentrations close to the major sources as well as

towards Central and Northeast regions. Elevated soil concentrations in Scandinavian soils provide further evidence of the potential of increased scavenging by forests and subsequent accumulation by organic-rich terrestrial surfaces. Initial model predictions have revealed a factor of 5-10 underestimation of lindane concentrations in the atmosphere. This is explained by an underestimation of source strength and/or an underestimation of European background levels. The model presented can further be used to predict deposition fluxes and chemical inventories, and it can also be adapted to provide characteristic travel distances and overall environmental persistence, which can be compared with other long-range transport prediction methods.

MacLeod, M.; Riley, W.J.; McKone, T. E. "Coupling global contaminant mass balance models with climate models: Transport to the Arctic as a case study." To be submitted to Environmental Science & Technology. 2004. LBNL-54847.

MacLeod, M.; McKone, T. E. "Comparing estimates of persistence and long-range transport potential among multimedia models." To be submitted to Environmental Science & Technology. 2004. LBNL-54848.

MacLeod, M.; McKone, T. E. "Identifying POP-like behavior in screening assessments of organic chemicals." To be submitted to Environmental Science & Technology, 2004. 2004. LBNL-54849.

MacLeod, M.; mckone T.E.; Hunt, J.R.; Mackay, D. "A mercury mass balance for the San Francisco Bay area: Development and application of a regional multi-species fugacity model." To be submitted to Chemosphere 2004. 2004. LBNL-54845.

MacLeod, M.; Mackay, D. "Modeling transport and deposition of contaminants to ecosystems of concern: A case study for the Laurentian Great Lakes." Environmental Pollution, Volume 128, Pages 241-250. 2004. LBNL-54149 .

Abstract. Transfer Efficiency (TE) is introduced as a model output that can be used to characterize the relative ability of chemicals to be transported in the environment and deposited to specific target ecosystems. We illustrate this concept by applying the Berkeley-Trent North American contaminant fate model (BETR North America) to identify organic chemicals with properties that result in efficient atmospheric transport and deposition to the Laurentian Great Lakes. By systematically applying the model to hypothetical organic chemicals that span a wide range of environmental partitioning properties, we identify combinations of properties that favor efficient transport and deposition to the Lakes. Five classes of chemicals are identified based on dominant transport and deposition pathways, and specific examples of chemicals in each class are identified and discussed. The role of vegetation in scavenging chemicals from the atmosphere is assessed, and found to have a negligible influence on transfer efficiency to the Great Lakes. Results indicate chemicals with octanol-water (Kow) and air-water (Kaw) partition coe.cients in the range of 105-107 and 10_4-10_1 combine efficient transport and deposition to the Great Lakes with potential for biaccumulation in the aquatic food web once they are deposited. A method of estimating the time scale for atmospheric transport and deposition process is suggested, and the effects of degrading reactions in the atmosphere and meteorological conditions on transport efficiency of different classes of chemicals are discussed. In total, this approach provides a method of identifying chemicals that are subject to long-range transport and deposition to specific target ecosystems as a result of their partitioning and persistence characteristics. Supported by an appropriate contaminant fate model, the approach can be applied to any target ecosystem of concern.

MacLeod, M.J.; McKone,T.E.; Foster, K.L.; Maddalena, R.L.; Parkerton, T.F.; Mackay, D. "Applications of contaminant fate and bioaccumulation models in assessing ecological risks of chemicals: a case study for gasoline hydrocarbons." To be submitted to Environmental Science & Technology. 2004. LBNL-54630 .

Abstract. Mass balance models of chemical fate and transport can be applied in ecological risk assessments for quantitative estimation of concentrations in air, water, soil and sediment. These concentrations can, in turn, be used to estimate organism exposures and ultimately internal tissue concentrations that can be compared to mode-of-action-based critical body residues that correspond to toxic effects. From this comparison, risks to the exposed organism can be evaluated. To illustrate the practical utility of fate models in ecological risk assessments of commercial products, the EQC

model and a simple screening level biouptake model including three organisms, (a bird, a mammal and a fish) is applied to gasoline. In this analysis, gasoline is divided into 24 components or "blocks" with similar environmental fate properties that are assumed to elicit ecotoxicity via a narcotic mode of action. Results demonstrate that differences in chemical properties and mode of entry into the environment lead to profound differences in the efficiency of transport from emission to target biota. We discuss the implications of these results and insights gained into the regional fate and ecological risks associated with gasoline. This approach is particularly suitable for assessing mixtures of components that have similar modes of action. We conclude that the model-based methodologies presented are widely applicable for screening level ecological risk assessments that support effective chemicals management.

Fenner, K.; MacLeod, M.; Stroebe, M.; Beyer, A.; Scheringer, M. "Relative importance of model and parameter uncertainty in models used for prediction of persistence and long-range transport potential of chemical pollutants." Proceedings of the International Environmental Modelling and Software Society Conference. 2004. LBNL-54846 .

Abstract. Overall persistence (POV) and long-range transport potential (LRTP) of chemicals are two indicators used in the context of precautionary chemical assessment. Multimedia fate models are used in research and regulatory contexts to calculate numerical indicators of POV and LRTP. The resulting indicator values exhibit uncertainty due to model uncertainty concerning model design and due to type A and B parameter uncertainty in the substance parameters. In this study, we compare the relative magnitude of parameter and model uncertainty for a large set of 3175 hypothetical chemicals that evenly cover the chemical parameter space and for eight different multimedia models available for the calculation of POV and LRTP. The assessment of the relative magnitude of the two types of uncertainty is important to direct further research and to inform the user on the level of confidence he can have in the model results. It is shown that, for POV, parameter uncertainty is larger than model uncertainty in most cases (78%), and that model uncertainty becomes more important for those chemicals which partition in considerable amounts into more than one environmental compartment. For LRTP, on the other hand, model uncertainty is higher than parameter uncertainty in most cases (75%). This dominance of model uncertainty can be explained with known differences in the model features. Uncertainty of POV can thus be reduced most effectively by improving data on degradation rate constants. For LRTP, the choice of the model that is best suited for the assessment purpose in question is most essential to reduce uncertainty.

Scheringer, M.; McKone T.E. "Is there a "forest filter effect" for airborne organic pollutants? A SERRA journal forum." Stochastic Environmental Research and Risk Assessment, Volume 17, Pages 229-230. 2003. LBNL-53456 .

Abstract. Almost a year ago, George Christakos, editor of the SERRA journal asked us individually as members of the editorial advisory board to organize for the journal a forum on a topic of current interest, involving some controversy, and of interest to the journal subscribers. In May 2002 both us found ourselves at conference in Vienna, Austria and in session with a rather lively discussion on the issue of whether forests can filter pollutants out of the atmosphere. Shortly after that we recognized that this would be a good topic for a SERRA forum and agreed to jointly organize this effort. Thus, we selected as topic for our forum the role of vegetation in controlling the transport, mobility, persistence, and partitioning of organic chemicals (not metals) in regional and global environments. In October 2002 we sent an e-mail to several of our colleagues posing two questions

McKone, T.E.; Bennett, D.H. "Chemical-specific representation of air-soil exchange and soil penetration in regional multimedia models." Environmental Science and Technology, Volume 37, Pages 3123-3132. 2003. LBNL-46693 .

Abstract. In multimedia mass-balance models, the soil compartment is an important sink as well as a conduit for transfers to vegetation and shallow groundwater. Here a novel approach for constructing soil transport algorithms for multimedia fate models is developed and evaluated. The resulting algorithms account for diffusion in gas and liquid components; advection in gas, liquid, or solid phases; and multiple transformation processes. They also provide an explicit quantification of the

characteristic soil penetration depth. We construct a compartment model using three and four soil layers to replicate with high reliability the flux and mass distribution obtained from the exact analytical solution describing the transient dispersion, advection, and transformation of chemicals in soil layers with different properties but a boundary condition at the air-soil surface. The soil compartment algorithms can be dynamically linked to other compartments (air, vegetation, ground water, surface water) in multimedia fate models. We demonstrate and evaluate the performance of the algorithms in a model with applications to benzene, benzo(a)pyrene, MTBE, TCDD, and tritium.

McKone, T.E.; MacLeod, M.J. "Tracking Multiple Pathways of Human Exposure to Persistent Multimedia Pollutants: Regional, Continental, and Global Scale Models." Annual Review of Environment and Resources, Volume 28, Pages 11. 2003. LBNL-52193 .

Abstract. Widespread observations of organic compounds in vegetation, soil, animals, and human tissue have motivated research on more accurate characterizations of chemical transport over regional, continental, and global scales. Efforts to assess human and ecosystem exposure to contaminants from multiple environmental media have been evolving over the last several decades. In this review we summarize the development and evolution of the multimedia mass-balance approach to pollutant fate and exposure evaluation and illustrate some of the calculations used in multimedia assessments. We describe the concepts that make possible the Mackay-type mass-balance compartment models. We describe ongoing efforts to use multimedia models to quantify human exposures. We use a series of case studies of varying complexity to illustrate capabilities and limitations of selected multimedia approaches. We look to the future and consider current challenges and opportunities in the field of multimedia contaminant fate and exposure modeling.

Marshall, J.; Riley, W.J.; McKone T.E.; Nazaroff, W.W. "Intake fraction of primary pollutants: Motor vehicle emissions in the South Coast Air Basin." Atmospheric Environment, Volume 37, Pages 3455-3468. 2003. LBNL-53457 .

Abstract. The intake fraction is de.ned for a speci.c species and emission source as the ratio of attributable population intake to total emissions. Focusing on Californias South Coast Air Basin (SoCAB) as a case study, we combine ambient monitoring data with time-activity patterns to estimate the population intake of carbon monoxide and benzene emitted from motor vehicles during 19961999. In addition to exposures to ambient concentrations, three microenvironments are considered in which the exposure concentration of motor vehicle emissions is higher than in ambient air: in and near vehicles, inside a building that is near a freeway, and inside a residence with an attached garage. Incorporating data on motor vehicle emissions estimated by the EMFAC2000 model, we estimate that the 15 million people in the SoCAB inhale 0.0030.009% (3485 per million, with a best estimate of 47 per million) of primary, nonreactive compounds emitted into the basin by motor vehicles. This population intake of primary motor vehicle emissions is approximately 50% higher than the average ambient concentration times the average breathing rate, owing to higher concentrations in the three microenvironments and also to the temporal and spatial correlation among breathing rates, concentrations, and population densities. The approach demonstrated here can inform policy decisions requiring a metric of population exposure to airborne pollutants.

McKone, T.E.; Thatcher, T.L.; Fisk, W.J.; Sextro, R.G.; Sohn, M.D.; Delp, W.W.; Riley, W.J. "Factors affecting the concentration of outdoor particles indoors: existing data and data needs." Proceedings of the Indoor Air 2002 Conference, Monterey, CA, Volume 1, Pages 176-181, Indoor Air 2002, Santa Cruz, CA. 2002. LBNL-49570 .

Abstract. Accurate characterization of particle concentrations indoors is critical to exposure assessments. It is estimated that indoor particle concentrations depend strongly on outdoor concentrations. For health scientists, knowledge of the factors that control the relationship of indoor particle concentrations to outdoor levels is particularly important. In this paper, we identify and evaluate sources of data for those factors that affect the transport to and concentration of outdoor particles indoors. To achieve this goal, we (i) identify and assemble relevant information on how particle

behavior during air leakage, HVAC operation, and particle filtration effects indoor particle concentration; (ii) review and evaluate the assembled information to distinguish data that are directly relevant to specific estimates of particle transport from those that are only indirectly useful; and (iii) provide a synthesis of the currently available information on building air- leakage parameters and their effect on indoor particle matter concentrations.

Maddalena, R.l.; McKone, T.E.; Kado, N.Y. "Exposure chamber measurements of mass transfer and partitioning at the plant/air interface." Environmental Science & Technology, Volume 36, Pages 3577-3585. 2002. LBNL-50569 .

Abstract. Dynamic measures of air and vegetation concentrations in an exposure chamber and a two-box mass balance model are used to quantify factors that control the rate and extent of chemical partitioning between vegetation and the atmosphere. A continuous stirred flow-through exposure chamber was used to investigate the gas-phase transfer of pollutants between air and plants. A probabilistic two-compartment mass-balance model of plant/air exchange within the exposure chamber was developed and used with measured concentrations from the chamber to simultaneously evaluate partitioning (Kpa), overall mass transfer across the plant/air interface (Upa) and loss rates in the atmosphere (Ra) and aboveground vegetation (Rp). The approach is demonstrated using mature Capsicum annuum (bell pepper) plants exposed to phenanthrene (PH), anthracene (AN), fluoranthene (FL) and pyrene (PY). Measured values of log Kpa (V[air]/V[fresh plant]) were 5.7, 5.7, 6.0 and 6.2 for PH, AN, FL and PY, respectively. Values of Upa (m d-1) under the conditions of this study ranged from 42 for PH to 119 for FL. After correcting for wall effects, the estimated reaction half-lives in air were 3, 9 and 25 hours for AN, FL and PY. Reaction half- lives in the plant compartment were 17, 6, 17 and 5 days for PH, AN, FL and PY. The combined use of exposure chamber measurements and models provides a robust tool for simultaneously measuring several different transfer factors that are important for modeling the uptake of pollutants into vegetation.

Bennett, D. H.; Mckone, T.E.; Evans, J.S.; Nazaroff, W.W.; Margni, M.D.; Jolliet, O.; Smith, K.R. "Defining intake fraction." Environmental Science & Technology, Volume 36, Pages 207A-211A, I. 2002. LBNL-50501 .

Abstract. Activities such as comparative risk analysis, life-cycle assessment, emissions trading and sustainable development are creating a growing demand for reliable and consistent information about the potential adverse effects of the thousands of chemicals released to the environment. This demand has fostered measurement and modeling efforts that link emissions to the resulting human exposures and subsequent health effects for a wide range of human products and activities, such manufacture and disposal of consumer goods, cooking, smoking, energy conversion, industrial production, and agriculture. For many pollutants, a preliminary estimate of the human health risk that is posed by an environmental release can be determined from the combination of three factors: (1) the quantity released; (2) the incremental intake per unit release; and (3) the risk of adverse effect per unit intake. This paper addresses the second term, the emissions-to-intake relationship. As discussed in a recent literature review, several researchers have independently developed similar approaches for relating source emissions to human intake for various pollutants and exposure pathways. Consequently, multiple terms, definitions, and units exist for what appears to be a single, yet multifaceted concept. But there are inconsistencies both in terminology and definitions among various researchers quantifying emissions-to-intake relationships. Differences in definitions leads to unnecessary complexity in comparing results from different research groups. Inconsistency in terminology when the same quantity is being calculated leads to further lack of transparency. We formed a working group and prepared this article to communicate our recommendations. for a set of terms and associated definitions that are descriptive, simple, accurate, and consistent both with common usage and usage in all relevant disciplines; are flexible to permit application over a broad range of potential uses; and reflect consensus among a large number of researchers. We propose the term intake fraction (iF) as the primary label for quantifying the emissions-to-intake relationship. Because the effort to employ intake fraction is in its early stages and is gaining momentum, now is the time to build consensus on terminology. Doing so will allow us to communicate more effectively both among ourselves and also with practitioners in related fields.

Bennett, D.H.; Margni, M.D.; McKone, T.E.; Jolliet, O. "Intake Fraction for Multimedia Pollutants: A Tool for Life Cycle Analysis and Comparative Risk Assessment." Risk Analysis, Volume 22, Pages 903-916. 2002. LBNL-47253.

Abstract. We employ the concept of Intake Fraction (iF) as an effective way to understand the source-to-dose relationship for pollutant emissions in Life Cycle Analysis (LCA) or comparative risk assessment. Intake fraction is the fraction of chemical mass emitted into the environment that eventually passes into a member of the population through inhalation, ingestion, or dermal exposure. To date, this concept has been primarily applied to pollutants whose primary route of exposure is inhalation. Here we extend the use of iF to multimedia pollutants with multiple exposure pathways. We use a level III multimedia model to calculate iF for TCDD and compare the results to one calculated from measured levels of dioxin toxic equivalents in the environment. We calculate iF for emissions to air and surface water for 244 chemicals. We correlate the primary exposure route with the magnitudes of the octanol-water partition coefficient, Kow, and of the air-water partitioning coefficient (dimensionless Henry constant), Kaw. This results in value ranges of Kow and Kaw where the chemical exposure route can be classified with limited input data requirements as primarily inhalation, primarily ingestion, or multi-pathway. For the inhalation and ingestion dominant pollutants, we also define empirical relationships based on chemical properties for quantifying dose fraction. The empirical relationships facilitate rapid evaluation of many chemicals in terms of the potential dose. By defining a theoretical upper limit for iF in a multimedia environment we find that iF calculations provide insight into the multimedia model algorithms and help identify unusual patterns of exposure and questionable exposure model results.

McKone, T.E.; A.B. Bodnar; E.G. Hertwich. "Development and evaluation of state-specific landscape data sets for multimedia source-to-dose models." 2001. LBNL-43722 .

MacLeod, M.; D.G. Woodfine; D. Mackay; T.E. McKone; D.H. Bennett; R.L. Maddalena. "BETR North America: A regionally segmented multimedia contaminant fate model for North America." Environmental Science & Pollution Research, Volume 8, Pages 156-163. 2001. LBNL-50571.

Abstract. We present the Berkeley-Trent North American contaminant fate model (BETR North America), a regionally segmented multimedia contaminant fate model based on the fugacity concept. The model is built on a framework that links contaminant fate models of individual regions, and is generally applicable to large, spatially heterogeneous areas. The North American environment is modeled as 24 ecological regions, within each region contaminant fate is described using a 7 compartment multimedia fugacity model including a vertically segmented atmosphere, freshwater, freshwater sediment, soil, coastal water and vegetation compartments. Inter-regional transport of contaminants in the atmosphere, freshwater and coastal water is described using a database of hydrological and meteorological data compiled with Geographical Information Systems (GIS) techniques. Steady-state and dynamic solutions to the 168 mass balance equations that make up the linked model for North America are discussed, and an illustrative case study of toxaphene transport from the southern United States to the Great Lakes Basin is presented. Regionally segmented models such as BETR North America can provide a critical link between evaluative models of long-range transport potential and contaminant concentrations observed in remote regions. The continent-scale mass balance calculated by the model provides a sound basis for evaluating long-range transport potential of organic pollutants, and formulation of continent scale management and regulatory strategies for chemicals.

Bennett, D.H.; Scheringer, M.; McKone, T.E.; Hungerbühler, K. "Predicting Long Range Transport: A Systematic Evaluation of Two Multimedia Transport Models." Environmental Science & Technology, Volume 35, Pages 1181-1189. 2001. LBNL-45690.

Bennett, D.H.; McKone, T.E.; Kastenberg, W.E.; Schwalbe, C.A. "Characteristic time, characteristic travel distance, and population based dose in a multimedia environment: A case study." Human & Ecological Risk Assessment: Theory and Practice, Volume Chapter 11, Pages 619-643, John Wiley and Sons. 2001. LBNL-45815 .

van de Meent, D.; T.E. McKone; Parkerton, T.; Matthies, M.; Scheringer, M.; Wania, F.; Purdy, R; Bennett, D.H. "Persistence and Transport Potential of Chemicals In A Multimedia Environment." Chapter 5 in the book, Persistence and Long-Range Transport of Organic Chemicals in the Environment:Guidelines and Criteria for Evaluation and Assessment, SETAC Press, Pensacola, FL. 2000. LBNL-43719.

Scheringer, M.; Bennett, D.H.; McKone, T. E.; Hugerbuhler, K. "Relationship between Persistence and Spatial Range of Environmental Chemicals. ACS Symposium Series 773." Persistent, Bioaccumulative, Toxic Chemicals II Assessment and New Chemicals, American Chemical Society, Washington, DC. 2000. LBNL-44343.

Maddalena, R.L.; McKone, T. E.; Hsieh, D.P.H.; Geng, S. "Influential Parameter Classification in Probabilistic Multimedia Models." Stochastic Environmental Research and Risk Assessment, Volume 15, Pages 1-17. 2000. LBNL-43335.

Bennett, D.H. "Population based dose models for multimedia chemicals with the potential for long range transport, May 2000." 2000. LBNL-45879 .

Bennett, D.H.; T. E. McKone; W. E. Kastenberg. "CART screening level analysis of characteristic time – a case study. ACS Symposium Series 773." Persistent, Bioaccumulative, Toxic Chemicals II Assessment and New Chemicals, American Chemical Society, Washington, DC. 2000. LBNL-43721.

Bennett, D.H.; T.E. McKone; W.E. Kastenberg. "Evaluating multimedia chemical persistence in a multimedia environment: A CART analysis." Environmental Toxicology and Chemistry, Volume 19, Pages 810-819. 2000. LBNL-42897.

Klecka, G.M.; D. Mackay; R.S. Boethling; T.E. McKone. "Evaluation of persistence and long-range transport of organic chemicals in the environment: summary of a SETAC Pellston workshop." Environmental Toxicology and Chemistry, Volume 18. 1999. LBNL-43720.

McKone, T.E.; A.B. Bodnar. "Improved Landfill Simulations Based on the CalTOX Framework." 1998. LBNL-41929.

Bennett, D.H.; James, A. L.; McKone, T. E.; Oldenburg, C. M. "On uncertainty in remediation analysis: variance propagation for subsurface transport to exposure modeling." Reliability Engineering and System Safety, Volume 62. 1998. LBNL-41335.

Bennett, D.H.; T.E. McKone; M. Matthies; W.E. Kastenberg. "General formulation of characteristic travel distance for semivolatile chemicals in a multimedia environment." Environmental Science and Technology, Volume 32, Pages 4023-4030. 1998. LBNL-43715.

9. Other

Koomey, J.; Craig, P.; Gadgil, A.J.; Lorenzetti, D. "Improving Forecasting: A plea for historical retrospectives." The Energy Journal, Volume 24, Pages 75-92. 2003. LBNL-52448 .

Abstract. One of the most striking things about forecasters is their lack of historical perspective. They rarely do retrospectives, even though looking back at past work can both illuminate the reasons for its success or failure, and improve the methodologies of current and future forecasts. One of the best and most famous retrospectives is that by Hans Landsberg, which investigates work conducted by Landsberg, Sam Schurr, and others. In this article, written mainly for model users, we highlight Landsberg's retrospective as a uniquely valuable contribution to improving forecasting methodologies. We also encourage model users to support such retrospectives more frequently. Finally, we give the current generation of analysts the kind of guidance we believe Landsberg and Sam Schurr would have offered about how to do retrospectives well.